Forest Service
U.S. DEPARTMENT OF AGRICULTUE

Forest Health Assessment &
Applied Sciences Team

FHAAST-2022-01

June 2022

Proceedings of the 7th North American Forest Insect Work Conference

Shaping Forests: Action in a Changing World

Rachel A. Arango (USDA Forest Service) and
Deepa S. Pureswaran (Canadian Forest Service), Technical Editors

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25-28 May 2021
Virtual

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Acknowledgements

We would like to acknowledge and congratulate Founders' Award recipient, Dr. Ken Raffa. We sincerely thank our plenary speakers, Shannon Lotthammer, Alexis Grinde, Sandy Liebhold, Eli Sagor, and Andrew Revkin. We are grateful to the University of Minnesota College of Continuing and Professional Studies for help with meeting planning and organization, specifically Suzanne Butler, Kristie Fisher, Paul Engels, and Rhonda Layer. Thanks to artist Aubree Kees for cover graphic design, Bernie Daigle for help with formatting the proceedings document, and Holly Munro and Peter Coffey for giving the workshop on insect macrophotography. Lastly, special thanks to Kristie Reddick of the "Bug Chicks" for an inspiring presentation about using insects in outreach.

Foreword

The North American Forest Insect Work Conference (NAFIWC) convenes every five years, bringing together members of the forest entomology community from universities, state and private forests, government, non-government organizations, and industry. This forum is intended for discussing current issues related to forest health, including novel or emerging insect pests and pathogens, plant-insect interactions, control, and management strategies, impacts of insect outbreaks, invasive species or disease agents among many others. This meeting also integrates the annual work conferences from the southern, western, north-central, and northeastern regions.

The theme for this year's meeting, "Shaping Forests: Action in a changing world" was fitting, not only within the context of climate change, but also in the unique need to hold these meetings virtually due to an ongoing, world-wide pandemic. Conference registration was 247, which is down from the usual 275-375 registrants at previous meetings, perhaps because of the virtual format. This year's program consisted of a poster session and student poster competition, three student paper competition sessions, 17 moderator-coordinated sessions, four open sessions, and a two-part workshop on insect photography. As this meeting was to be held in Duluth, Minnesota before the decision was made to shift to a virtual platform, a number of presentations and symposia were centered around the Midwest region including a session focused on forest insect and disease challenges in Minnesota as well as plenary presentations from Shannon Lotthammer (Assistant Forestry Commissioner for the Minnesota Department of Natural Resources), Alexis Grinde (Natural Resources Research Institute, UMN-Duluth), and Eli Sagor (UMN, Cloquet Forestry Center).

These proceedings are organized into four main sections based on program format: Founders memorial presentation and plenary addresses, concurrent sessions, student presentations, and poster abstracts. Except for poster presentations, all presenting authors were invited to submit extended abstracts for inclusion in the meeting proceedings document. The materials presented here for each session were compiled by, or with the assistance of, individual session organizers.

Contents

Founders Memorial Presentation

Appreciating our careers as brief snapshots of forests, insects, and human values, but also an opportunity to help shape their shared trajectory

Ken Raffa, Professor Emeritus,
University of Wisconsin–Madison

Introduction

I'd like to thank the WFIWC Awards Committee for presenting me with this recognition, the folks who took time from their busy schedules to write supporting letters on my behalf, and the NAFIWC organizers for hosting me.

More than anyone I'd like to thank Anne, my wife of over 40 years, best friend, and love of my life. Anne has very graciously opened our home to my students and colleagues. Heartfelt thanks goes to my daughters Annie & Cathy, who've supported every step of my journey and often accompanied me in the field and to meetings. Plus, they now provide my IT support.

I'd also like to thank my wonderful grad students and postdoctoral associates who provided the energy, enthusiasm, and creativity behind our work. I'm continually learning from them. Likewise, I'm grateful for the outstanding collaborators with whom I've had the pleasure to work. They brought expertise from a wide range of disciplines, and it's only because of their contributions that I've been able to undertake the scientific and management approaches I have.

Major strides in forest entomology over the course of my career

Forest entomology has undergone enormous strides since my first experiences as a Forest Service tech in 1973. I view these strides as coming in three major forms: methodological, disciplinary, and cultural.

Methodological

Some of the major methodological advances include molecular analyses, geographic information systems, chemical analyses, spatially explicit statistic, and bioinformatics among others. Once the realm of high hopes among specialists, these tools are now widely accessible.

Together these tools have enabled two broad advancements: first, we're far better positioned to conduct cross-scalar studies than ever before. Historically, studies were necessarily conducted at just one level of scale, but now it's common to see rigorous experiments that span the molecular through landscape levels. Second, thanks to these advances we're seeing more and more high-quality studies that effectively link pattern and process, and better position us to develop more effective management and environmentally judicious strategies.

Disciplinary

A wide range of scientific disciplines that overlap forest entomology have made enormous leaps over this same time course. Foremost among these are plant-herbivore interactions, symbioses, genetics and landscape ecology.

When I first started, trees were viewed largely as passive defenseless entities, almost like the 'damsels in distress' of old folklore. Now we know trees are bad-asses that usually kill or drive off their enemies. They stand their ground and do every horrible thing imaginable to insects. Then they go after their families and associates. We now recognize that insect outbreaks are the exception rather than the rule, and these outbreaks are often useful signals of important changes in the environment.

Similar changes have occurred in the area of symbioses. Early studies focused almost entirely on vector relationships, which are clearly very important. Symbiotic associations were usually envisioned as bipartite and unifunctional. We now recognize that all aspects of insect biology rely on complex relationships with a broad array of microorganisms, each of which has its own agenda. Important symbiotic relationships can vary enormously across systems in their modes of vertical versus environmental transmission, context dependency, substitutability, and redundancy.

Population models, while providing good descriptions of numerical changes, historically lacked the capacity to realistically incorporate genetic variation. Scientists fully appreciated that individuals varied, but there were few tools to incorporate variability in mechanistically grounded ways. Now, thanks largely to advances in molecular tools, forest entomologists have identified and quantified important sources of genetic variation among insects, their host trees, and their symbionts into our understanding of forest health and our capacity for management.

Advances in landscape ecology have allowed us to develop models that are both conceptually and computationally more advanced than previous approaches. These landscape models have demonstrated substantial management applications such as the gypsy moth Slow the Spread program, models of climate-driven range expansions, and our improved ability to forecast spread rates of invasive species. Forest entomologists are also making important contributions to disturbance ecology, helping key distinctions between the rapid genetic and population feedback dynamics of biotic from abiotic agents become better appreciated.

Cultural

During the 1970s and even 1980s forest entomology, and for that matter science as a whole, provided few opportunities for women. The early photographs of our meetings bear this out. Now, women not only make up half of our conference program, but they have also held all of our professional societies' major offices and positions of leadership, and are at the forefront of our research, education, and outreach missions. When I retired from University of Wisconsin–Madison, my department was 50% female and our chair, dean, and chancellor, i.e., the complete chain of command, were women. There have likewise been some improvements in membership among minority groups. But here there is still a very long way to go. An encouraging step in this direction is that forest entomologists at a number of universities have fostered partnerships with minority institutions, organizations, and students.

A second cultural change is that our profession has become increasingly interdisciplinary. Interdisciplinary collaboration has always been a strength of forest entomology, but the range of these disciplines has broadened. Initially this expanding range reflected the rapidly advancing scientific methodologies described above, with greater collaboration with geneticists, chemists, microbiologists, and statisticians. More recently, these collaborations have expanded even further to encompass human dimensions, and include expertise in economics, sociology, environmental history, and communication. The mission of forest entomology has also become more multi-purposed. For example, in addition to contributing to what traditionally has been termed forest protection, forest entomologists now devote substantial attention to ecological services and the urban environment. The future vitality of forest entomology is closely linked to how well it serves, and its contributions are appreciated by our largely urban/suburban population.

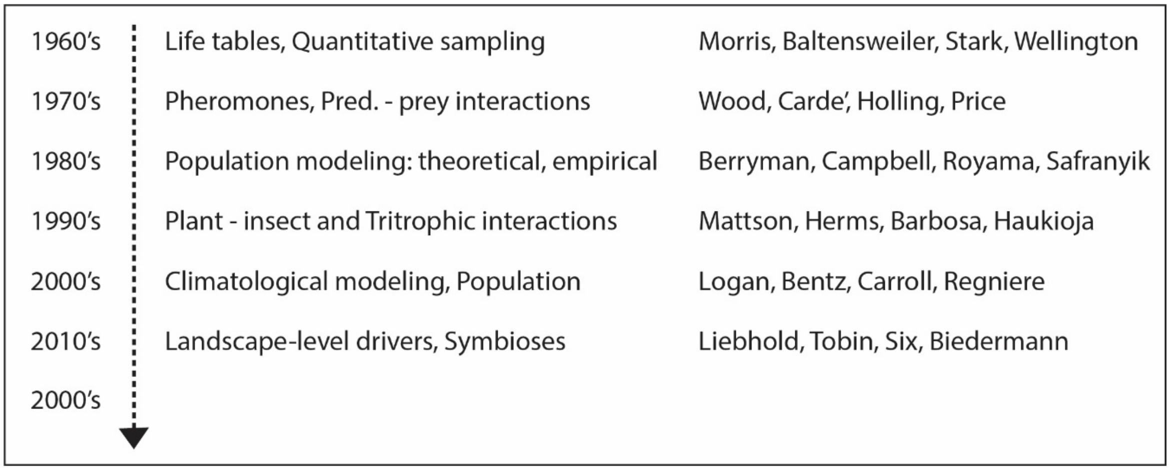
Finally, when I began my career there were strong divisions between what was then termed 'basic' and 'applied' research. Those barriers have largely broken down, which I consider a highly positive change. In fact, I hope I contributed to that trend. These barriers lessened the flow of ideas and also limited publication and grant opportunities. I think a big reason for this blending is the changing nature of the challenges we face; whereas 'applied' once referred solely to the protection of resources utilizable as forest products, it now encompasses some of our most pressing environmental issues as well. Scientists who might not have considered themselves applied ecologists are bringing their efforts and expertise to issues such as biological invasions, and scientists who viewed their primary mission as forest protection are deeply immersed in changing outbreak dynamics arising from climate change, to give just two of many examples. There is still progress to be made. For example, a recent bibliometric analysis found high asymmetry in citations of invasive forest insect pest research, with biological control professionals frequently citing invasion ecologists but the reciprocal being proportionately less common (Schulz et al. 2021).

Contributions of forest entomologists to general ecology and entomology

As we prepare to better address the intensifying current and future challenges posed by climate change, land use alteration, invasive species, and interfaces between land use sectors, I think it is valuable to also employ a historical framework. This can aid us in evaluating forest entomology's prior contributions and more importantly identify broad features of our system that fostered those contributions. My hope is that we can increase the pace of positive changes while at the same time continue to draw upon the strengths and advantages that our system offers.

Historical Contributions

What's striking is that forest entomologists have been at the forefront of each of these major advances (Figure 1). For example, during the 1960s, population biology was becoming less the sole realm of mathematicians and theoreticians, and more real world oriented. At the forefront of these broad advances were forest entomologists such as Robert Morris, Bill Wellington, and Werner Baltensweiler. Similarly, there was an explosion of knowledge about insect pheromones and chemical signaling during the 1970s. Again, forest entomologists such as Dave Wood and others were at the forefront. Some of the first, if the not the first, illustrations of predator attraction to herbivore pheromones, microbial symbiont production of insect pheromones, parasitoid exploitation of symbiont-emitting volatiles, stereochemical roles in interspecific population structure, and orientation to point sources in the field came from studies with forest insects. Likewise, our knowledge of predator-prey and tritrophic interactions is largely founded on the work of Buzz Holling with sawflies, Ken Royama with eastern spruce budworm, and Peter Price with parasitoids. During the 1980s, forest entomologists such as Alan Berryman, Robert Campbell, and Les Safranyik emerged as leaders on population eruptions and some of the earliest and most enduring models of bimodal equilibria. As we moved into the 1990s, plant-herbivore interactions became a major focus of general ecology and entomology. Two of the all-time most cited papers in the entire field of plant-herbivore interactions are by forest entomologists, Bill Mattson’s chapter on the role of nitrogen (3860), and the Growth Differentiation Balance Hypothesis (4202) by Dan Herms and Bill Mattson. The field of longterm induction to herbivory was largely introduced by forest entomologists such as Erkki Haukioja. The trend continues through the present.



1960’s	Life tables, Quantitative sampling	Morris, Baltensweiler, Stark, Wellington
1970’s	Pheromones, Pred. - prey interactions	Wood, Carde’, Holling, Price
1980’s	Population modeling: theoretical, empirical	Berryman, Campbell, Royama, Safranyik
1990’s	Plant - insect and Tritrophic interactions	Mattson, Herms, Barbosa, Haukioja
2000’s	Climatological modeling, Population	Logan, Bentz, Carroll, Regniere
2010’s	Landscape-level drivers, Symbioses	Liebhold, Tobin, Six, Biedermann
2000’s		

Figure 1. Examples of forest entomology contributions to general ecology & entomology.

The outsized contributions by forest entomologists relative to their rather small numbers and funding opportunities is reflected in our professional societies. If you look at awards by the Entomological Society of America, for example, you’ll see an over-representation of forest entomology graduate students and professionals. As an illustration, over the last five years, forest entomologists have averaged a newly inducted lifetime Fellow per year.

So why is it that forest entomologists have so consistently punched above their weight? Are we smarter than everyone else? Speaking only for myself, I think we can eliminate that possibility quite easily. Instead, I think there are features of our system, our culture, and our mission that foster doing impactful science.

Features of our system and community that foster doing impactful science

Clearly, working with forests poses challenges. The size and lifespan of trees pose logistic constraints to controlled glasshouse or laboratory studies. Some insects are almost entirely associated with mature trees that differ ontogenetically from experimentally more amenable seedlings and saplings. The economics and hence political backing have historically led to lower financial support than other sectors thereby resulting in lags in baseline data. Human-associated values are complex and sometimes contradictory, field studies may be randomly disrupted by fire, weather extremes, or changes in land ownership, and natural ecosystems are so diverse and variable that true replication is difficult to achieve.

Despite the above disadvantages, there are substantial advantages to working with forest ecosystems. I identify below six features of our system and community that I believe foster doing impactful science and have contributed to the historical contributions described above.

The relatively less manipulated nature of our ecosystems

I think a major driver behind the insights gained by forest entomologists is that the systems we study have generally undergone substantially less manipulation than the systems studied by our counterparts in agricultural, urban, and laboratory environments. The gene pools of plants, insects, and microbes are far less manipulated in forests, the potential number of interactions is less constrained by prior manipulation and manicuring of the environment and human-induced disturbances are far less frequent. All of that gives us the opportunity to see nature in a less filtered form and thus to peer more directly into innate ecological processes. That in turn heightens what can be gained from sound observation. Not having the system turned over every year allows us to conduct long-term studies, and fosters a long-term view.

Remoteness and scale of forests

The remoteness and scale of forests are often viewed as obstacles to research and to implementing well-controlled experiments. But they also help foster greater independence during graduate education. As we all know, working as a graduate student in forests is quite different from other forms of graduate study. You're often far removed from your major professor, and for long periods of time. You may have no way of communicating with your advisor, especially in the pre-digital era. No matter how well you plan things back in the lab, things never go according to the playbook in the field. So you learn to think on your feet.

At the same time, that remoteness and scale foster teamwork. The best students figure out quickly that by helping on each other's projects they can accomplish more. They come up with creative ways to divvy up the work. Put at its most fundamental level, trees are too large for any one person to lift. You have to work together. That sense of teamwork segues into our permanent positions. Most of the insects we deal with span geographic scales far beyond our physical capabilities, so we seek out partners who can help us collectively encompass as much of those geographic and host ranges as possible. These broad-scale, multi-participant, uniformly performed experiments can generate a lot of valuable information in a short time (e.g., Erbilgin et al. 2007).

Finally, we aren't under the same economic pressures as our colleagues in agricultural and urban environments. Trees just aren't worth the money to justify intensive management such as pesticides. So, we've always needed to find alternate solutions to pest pressures. This has favored long-term approaches based on understanding feedbacks.

Synergy between university and government agency missions, approaches, and capabilities

Another major factor for forest entomology's success is the complementary missions, approaches, and capabilities of universities and government agencies (e.g., US & Can. Forest Service, state & provincial departments of natural resources). The universities provide graduate and undergraduate students who bring enormous energy, idealism, new outlooks and the latest methodologies. The government agencies bring consistency and historical memory, often in the form of long-term non-Ph.D. employees who have tremendous hands-on familiarity. Think of any successful Forest Service research station, and you're likely to recall some of these individuals as much as you think of the lead scientists.

The missions and capabilities of universities and forestry agencies are often synergistic. For example, government forestry agencies are often able to do large-scale and long-term manipulations that university scientists living on short-term extramural grants couldn't achieve. In turn, universities are often able to address more basic questions than government biologists can devote their time to. This fosters a synergism that begins during graduate training. I'd be willing to bet that almost all, if not all, forest entomologists interacted extensively with federal and state/provincial agencies while they were in graduate school. Certainly agricultural university and Agricultural Research Service scientists collaborate, but I've always felt there was higher overlap between their missions than in forestry.

Physicality of field work, and accompanying road trips, engender a spirit of collegiality, familiarity, and mutual appreciation

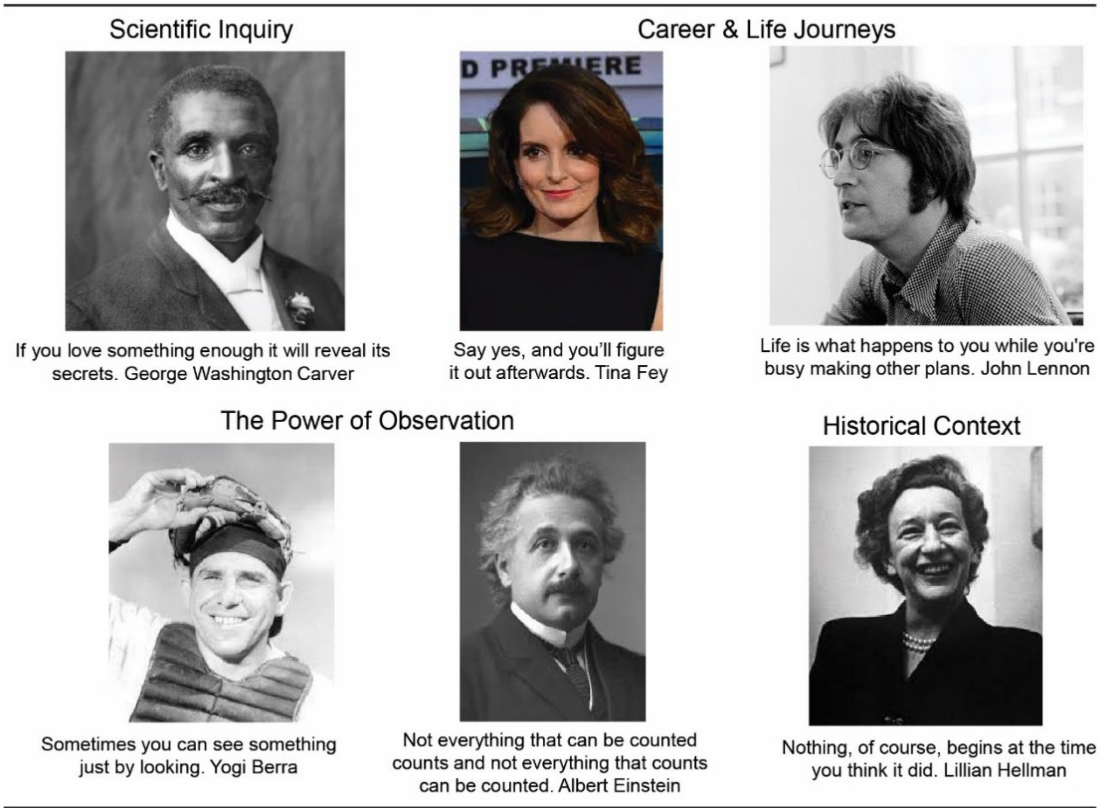
The physical nature of forest entomology builds a special bond. People are drawn to our field because they enjoy being outdoors. We learn each other's strengths and weaknesses, and professors and students interact on equal terms. It's an environment that leads to shared encounters with everything from mosquitoes to bears. Lodging conditions are often primitive, and require sharing, resourcefulness, and accommodation.

With field work comes long road trips. There's something special about the environment of a lone pickup truck moving across the landscape after a long, draining day in the field. It gives professors a chance to listen and learn about their student's aspirations and fears, and to share their own journey. Road trips require compromising on musical tastes and are not the time for losing yourself in your ear-buds. You also learn about each other's idiosyncrasies, which is what make people interesting and fun. Even the biggest health enthusiast may have no will power over road-trip junk food. My inability to drive past a historical marker is well known, and probably more than a bit annoying. During a road trip, you learn everything about each other from your philosophy of life to bladder capacity.

We're constantly enriched by the sheer beauty and wonder of our system

We also have the special advantage of the sheer beauty of our system. We're often taught in our undergraduate studies to view science as a strictly formulaic, dispassionate undertaking. But working close to nature is a special treat that stimulates our creativity, so we should embrace that beauty. I’ve always told my students that I’ve never had an original thought indoors. No matter how many things might go wrong in the field; the chainsaw won’t start, the insects aren’t flying, and the maps are all wrong, a bad day in the field is still better than a good day in the office.

I think the aesthetics of science is best captured by the quote from George Washington Carver, which I first encountered in grad school (Figure 2). The idea of approaching scientific inquiry as a romance between the scientist and their subject is very powerful. It’s too easy in a highly controlled lab environments to forget that, and to feel we need to wring the truth out of our test subject, and to almost feel betrayed when it doesn’t behave as we expect. Instead, when you work in nature you enjoy both the awe and the whimsy. When I interviewed potential grad students, I’d always tell them ‘If you’re good with the fact that Mother Nature always gets the last laugh, you’re going to love this. If you’re not, you’ll be miserable”.



If you love something enough it will reveal its secrets. George Washington Carver

Say yes, and you’ll figure it out afterwards. Tina Fey

Life is what happens to you while you're busy making other plans. John Lennon

Sometimes you can see something just by looking. Yogi Berra

Not everything that can be counted counts and not everything that counts can be counted. Albert Einstein

Nothing, of course, begins at the time you think it did. Lillian Hellman

Figure 2. Some reflections to consider.

<u>We’re accustomed to being wrong</u>

The experience of doing fieldwork amidst Nature’s whimsy brings me to my final point: forest entomologists are accustomed to being wrong. It starts in the field, when you fell your first tree backwards, take the wrong turn, get your truck stuck in the mud, or forget to bring the toilet paper. We learn to not take ourselves too seriously. This engenders a spirit of understanding and empathy.

When you work with Nature, if you can only explain a small portion of the variation even a small portion of the time, that's quite an accomplishment. Our conclusions are rarely as robust as we first envisioned and this happens repeatedly over the course of our careers. This leads to a particular psychology. When we read a result that differs from our own, our first instinct is to ask 'I wonder what's different about that site, that environment, that management history, etc. from my own?' It stimulates our curiosity. That curiosity emboldens us to reach out and launch inter-regional comparisons, some of which have been the most rewarding projects of my career.

Again, that differs from a highly controlled lab environment where different results may seem more threatening, and more easily interpreted as someone must be wrong. We know all too well from our own setbacks that Nature is too complicated to yield many fully right or fully wrong answers.

Reflections on doing teaching, research, and outreach

In hindsight, a career looks like it's been planned. But in reality (with perhaps some exceptions), it's more a matter of taking advantage of opportunities, learning from mistakes, benefitting from good teachers and role models in all walks and stations of life, recognizing the environments in which and the people with whom you're most likely to make best use of your aptitudes, and life-long learning. In my case a career that might appear deceptively cohesive through its government, industry, and academia lines began with a one-question interview of whether I feared being in low-flying aircraft in mountainous terrain, and progressed through being recruited to protect a university woodlot from adjacent football stadium fans relieving themselves during halftime, deciding to stay in my doctoral program because I was unsure my car could make the return cross-country trip, accepting an agricultural research position for personal reasons of family proximity, and a series of coincidences that led the University of Wisconsin–Madison entomology faculty to take a chance on me.

The broad subjects of teaching, research, and outreach over the course of a career would be far too much to cover here. Instead, I'd like to just highlight one or two selected points under each.

Teaching

When you really stand back, the most meaningful contributions a professor can make is as a teacher – of undergraduates who take their courses, do independent studies, or work in their lab, of graduate students, and of postdoctoral associates.

My experience is that the most effective classes are those that integrate lecture, lab, and field. Seeing the same thing in different modalities greatly reinforces learning. Also, some students who may not perform particularly well in the classroom might shine in the field. I also think there's benefit to teaching integrated insect & disease courses. For one, students have to think about the full range of possibilities when they diagnose symptoms: they can't say 'well it's first semester so it must be an insect'. Also, the best course of action for dealing with an insect might be a very poor idea for dealing with a pathogen. So, an integrated course requires students to contend effectively with the tradeoffs.

I couldn’t possibly be more proud of my grad students. They’ve published lots of great papers and gone on to run terrific programs. But there are two things I’m particularly proud of. First, they’ve each become important contributors in a wide variety of ways of their own choosing. Each has blazed their own path. Second, my students have always helped each other. I always knew I could call a former student and say I have a new student who could benefit from a technique they had developed. They’d inevitably invite them into their home in their new location to help get them started… and have a few drinks and tell embarrassing stories about me as well. When I recruited graduate students, I looked for people who had multiple life experiences, rather than straight A’s. I’d ask them about their research, but my most important question was ‘what went wrong and what did you do about it’? I wanted to see how they handled setbacks, because that’s mostly what science is. Learning how a student decides when the best course is to try again, make minor modifications, make a drastic change, or seek help tells me more than their GPA.

In today’s competitive job market, my advice to grad students is it’s not enough to be highly productive, you also need a valued toolbox. With institutions downsizing, department members are not just looking for high performers, they’re also looking for collaborators. That toolbox could be statistics, analytical chemistry, molecular techniques, etc. So I’ve always directed each student to become better than me at something – or as one dear colleague said ‘well in your case Ken, that’s not particularly difficult!’

Research

Being a forest entomologist typically involves working on a wide range of insects, habitats, management regimes, and subject areas. That provides outstanding opportunities for integration, synthesis, and a long-term building, rejection, and recasting of ideas. Across this diversity of taxa and approaches, I pursued one overriding theme─understanding processes that drive populations. My career-long goal was to help link pattern and process by repeatedly asking three questions of each system: 1) What factors mediate the key interactions that drive populations? 2) Where are the feedbacks and how do they function? 3) How can we manipulate these interactions and feedbacks to keep insects below damaging densities and likewise foster resiliency?

I mention the overarching questions in order to introduce what I feel is a major challenge facing young forest entomologists today. Although invasive species pose one of the most important issues of our time, the continual barrage of new arrivals can make it difficult to establish continuity. Scientists must follow funding sources and funding sources follow each new introduction, often in an urgent emergency context. It’s important and in our best abiding interests for funding agencies to also provide opportunities for beginning scientists to establish coherent programs that pursue a long-term vision, such as the one that benefitted me.

Outreach

Of my many outreach and service activities, my most rewarding has been in K-12 education. I think it is vital to engage new generations during their formative years, demystifying science, and making science more accessible to under-represented groups. Twenty years ago, my wife Anne, who is a Reading Specialist had the vision to not just teach kids about insects, but rather use insects to make children want to become readers. Her Title One section was for kids in the lowest percentiles. Kids have specialized needs and low reading proficiency for reasons as wide-ranging as dyslexia, poverty, and not speaking English as their first language. So as part of our Reading Bug program, weeks before I came Anne would start her students with matching exercises, in which they learned to connect action words like jump and sting with names and pictures of various insects. She had them write stories, poems, and haikus about insects, and compose questions. Wanting to know more about insects made kids want to, and become confident, they could read. Based on their work it's hard to believe these kids are deemed underperformers by conventional standards. Their questions were insightful, and their poems about insects were often very personal and based on lived experiences.

I think children are especially drawn to insects for a couple of reasons. First, in a child's world almost everything is bigger than them. So kids feel very protective toward insects. Also, kids can sense that adults are annoyed by insects, and that's just how some of these marginalized children feel looked upon. So they see insects as a thumb in the adult world's eye, as rebels. Insects have street cred!

Lessons Learned

Over the course of my nearly 50-year career, which is actually an inconsequential period over the span during which insects and trees have been interacting, I've learned a few lessons. Sharing some of these lessons offers me the best opportunity to translate that inconsequential time period into positive effects.

The continued benefits of sound observation

Even in this age of advanced molecular methodologies, powerful remote sensing, and computer-driven data mining, there is still tremendous benefit to studious observation. Observations are most effective when they are curiosity-driven, grounded in an appreciation of when and how best to appropriately apply quantitative methods, and contextualized within a historical framework. Historical framework can be valuable both in the short term such as disturbance regimes, management programs and oral history, and in the long term, such as evolutionary selective pressures, diversification, biogeography and glaciation patterns.

One personal example of the value of observation is how our work on interactions between bark beetles and bacteria was launched. I hired a postdoctoral associate, Yasmin Cardoza, who had a strong background in chemical ecology. Yasmin had never worked with bark beetles, so she'd carefully watch the adults tunnel galleries in phloem sandwiches beneath plexiglas. One morning she said she noticed that as spruce beetles dig, they egest droplets and smear them along the gallery with their tarsi. I'd never seen this. Or more to the point I'd never noticed it. Yasmin speculated that these egestions might contain bacteria that produce compounds that protect the eggs from antagonistic fungi. Her follow-up experiments demonstrated just that (Cardoza et al. 2006). That finding led to a whole series of new directions, grad student programs, collaborations, and papers. It all started with Yasmin's astute observations.

Ingredients of effective collaboration

As I mentioned, many of my papers, and certainly my best ones, involved collaborations with other scientists, often from other fields. Many of these collaborations spanned many years. I think there are several key ingredients to fruitful, long-term collaborations. I list the most important ones below:

1. Overlapping interests but complementary skill sets: Complementary skill sets brought to a common question make the difference between whether contributions are synergistic or just additive.
2. Each partner has their own 'big picture', of which this collaboration is at its center: At first this might sound selfish, but you want big-picture people as your collaborators. An example is my wonderful and fruitful collaboration with the bacteriologist Jo Handelsman. I was interested in how gypsy moths contend with tree toxins, especially whether gut bacteria might be involved. She was interested in the bacterial communities of extreme environments; fortuitously what could be more extreme than a living gut with a pH of 8-10? We published over 20 papers together over 12 years.
3. Joint hierarchical approach to problem solving, mutual levels of engagement, but complementary approaches to inference: It's important to find collaborators who have similar approaches to logical progression of experimentation and decision-making, but also different degrees of generalizing and risk-taking. Again, pointing to my collaborations with Jo Handelsman, she was more intellectually assertive than I in deducing the role gut bacteria play in gypsy moth susceptibility to Bt. Thanks to her, the resulting paper (Broderick et al. 2006) has been cited over 500 times, the main conclusions have been validated by several independent labs, and the grad student is now a tenure-track professor at a highly prestigious institution.
4. Genuinely enjoy who each other are, and mutually benefit from debating different perspectives: Ultimately, your collaborator needs to be someone you enjoy working and being with, someone you can trust and with whom you can share your ups and downs. If your collaborator reads texts or emails while you're meeting, run. But if your collaborator challenges your assertions and proposes alternate directions, stay. Two of the best lessons I learned (I can't verify the original source) are '*If two people agree on everything, you have one too many people on the project'*, and *'If you want something done, ask a busy person'.*

Notice what is not on this list is administrative structure. Administrators spend countless hours organizing and re-organizing managerial structures. It doesn't matter. People seek out and find the people they most want to work with. It's organic and cannot be imposed from above.

Explicitly identify feedbacks, thresholds, and cross-scale interactions

Most ecological relationships prove to be multifactoral. So, it's more useful to design experiments from the very beginning with the intention of detecting how processes interact than accessing *post hoc* which is most important. This is especially true for systems in which key thresholds determine qualitatively different outcomes structured by quantitative inputs.
My graduate supervisor Alan Berryman, a quantitative modeler with very strong statistical skills, once reminded me that the reason we typically apply linear models is that they're more amenable to analysis, not necessarily that they emulate reality. He then went on to say that

applying linear models to threshold-based systems was akin to correlating the number of photons emitting from a lamp with the vertical movement of the wall switch. It just doesn't function that way (but, I would add, a rheostat does so applicability is always system-specific).

Keeping Alan's admonition in mind has been helpful throughout my next 40 years of experimental biology. For example, in the case of bark beetles Boone et al. (2011) found '*Host defenses were major constraints when mountain pine beetle populations were low, but inconsequential after stand-level densities surpassed a critical threshold*'. Or more generally '*not only does correlation not necessarily imply causation as is widely recognized, but in systems … with cross-scale, threshold-dominated interactions, lack of correlations does not necessarily imply lack of causation, because important "signatures" may be erased as various thresholds are surpassed'* (Raffa et al. 2008).

The final suggestion I'd like to make about experimental design is to recognize the strengths and weaknesses of various contexts rather than view any one as innately superior. Put simply, there is a natural and healthy tension between the reality of the field and the precision of the laboratory. Major contributions, and also unjustified extrapolations, come from both domains, so it's always worthwhile to reflect upon where along that gradient our current work resides and ultimately strive to bridge the positive assets of each.

View native insects as functioning residents not enemies of forests

When I first started in forest entomology, classic texts had titles such as 'Insect Enemies of Eastern Forests', 'Insect Enemies of Western Forests', etc. But native insects aren't enemies of forests, they're part of the forest. Without arthropods, we cannot even conceive of well-functioning ecosystem processes such as decomposition, nutrient cycling, pollination, adequate food resources for wildlife and fish, etc. Chitin is as much a part of the forest as is cellulose. That is not to say insects do not interfere with some of our management objectives and exert significant hardship, but such harm is simply because we're competing for the same resource. From a life history standpoint *'Bark beetles and humans are both in the business of converting trees into homes, making some conflict of interest inevitable'* (Raffa et al. 2015).

The notion of competing interests, rather than assigning enemy status should guide our management approaches. Specifically, management should be aimed at keeping insects' resource utilization within the bounds of well-defined land use objectives, not control for its own sake. Perhaps we should have a book called 'Insect Frenemies of Forests'.

Science is a human undertaking

Even though the process of science is objective, the questions we ask, the settings in which we are most creative, and the scales at which our aptitudes are best realized derive from early formative experiences of our environmental surroundings, historical context, family, and culture. In my own case as a grandson of immigrants and first-generation college student, my career as an applied ecologist reflects a mixture of blue-collar upbringing, childhood free-range roaming of forests, Jonas Salk and the conquest of polio, Rachel Carson and the admonition of environmental harm that unbridled technology can bring, and 1950s Sci-Fi movies in which the scientist saved the day by ascertaining the (in some cases human-induced) monster's weak link where brute force defenses failed. It didn't hurt my aspirations that the scientist in these movies typically achieved fame and fortune and won the beautiful woman. So the fingerprint of each scientist's personal backstory in their discoveries and manner of doing science should be celebrated.

Major challenges facing forest entomology

Finally, forest entomology has an important role to play in all of the major environmental and natural resources problems that confront us. Some of the most pressing issues include climate change, invasive species, and land use alteration. But I see four over-arching challenges that impact how well forest entomology can address these issues:

1. <u>Multiple and competing values generate different desired outcomes</u>
   First, humans derive multiple and often competing values from forests. If you think about a cornfield for example, people may have different opinions on how to manage it – insecticides, resistance varieties, GMOs, biocontrol, etc. But there's no disagreement about what a cornfield is for. That's not so for forests. When people see a forest, some see a livelihood and a source of forest products that benefit our quality of life. But others see recreation, which itself comes in many different forms such as backpacking, hunting, fishing, and aesthetic appreciation. Still others see a critical source of ecosystem services, such as harboring biodiversity, sequestering carbon, and fostering hydrology and soil quality. When people argue over what management tactics to employ against insects in national forests for example, there is often an unspoken underlying disagreement over what they feel that forest is 'for'. But it's pointless to design management tactics without first agreeing on desired outcomes.

2. <u>Disconnect between ideal spatiotemporal scales for management vs. actual scales of political borders and administrative terms</u>
   Disagreements over desired outcomes lead to the second problem. To manage forests judiciously we need to do so on a landscape scale, and over a span of many decades. But political boundaries often abut against each other on a much finer spatial scale, and new administrations appear every couple of years and totally reverse prior policies, regulations, and goals. The rate at which political leaders change forest policy objectives is equivalent, on a relative time scale, to a farmer changing their goals for a particular field every week. Anyone would recognize such frequent agricultural changes as completely unworkable. We somehow have to get the message out that forest management requires a longterm and birds-eye view.

3. <u>Anthropogenic change: To what extent can past lessons be applied vs. to what extent are they poorly applicable to future conditions?</u>
   The challenges I've described are accentuated by the fact that everything is occurring on a changing template. Temperature, precipitation patterns, species distributions, and habitat are all undergoing unprecedented rates of change. So the question becomes: How do we decide when to maximally apply what we've learned, vs. realize it's no longer applicable? We want to avoid reinventing the wheel, but also we don't want to be like a general who employs the lessons of the last war. Answering this question will require substantial theoretical and empirical development within a dynamic framework.

4. Shifting societal attitudes on scientific method, facts, objective reality
   Finally, scientists have always had to deal with a relatively uninformed public. But now we must also deal with a deliberately and strategically misinformed public. Due to a skilled and constant barrage of misinformation, much of our public now views the results of scientific studies as just one more form of belief, and disputes the very notion of provable facts. The USA's response to COVID-19 provides a current illustration. Even though vaccine development was a triumph of both fundamental and directed research by universities, government agencies, and corporations, the sociopolitical response to science-based guidance was abysmal and literally fatal. Fortunately, a number of forest entomologists are actively engaged in providing solid updated information using both traditional formats and digital communication such as podcasts, Ted Talks, social media, etc. That's a hopeful trend worthy of our utmost support, recognition, and reward.

Link to Ken Raffa's recorded Founder's Award presentation: https://youtu.be/mhYo5ZRpX54

Acknowledgments: Helpful comments by Rachel Arango (USDA FS), Richard Hofstetter (NAU), and Lynne Rieske (U KY) are greatly appreciated.

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PLENARY ADDRESSES

Minnesota’s forests in a changing world

Shannon Lotthammer, Assistant Commissioner,
Minnesota Department of Natural Resources

EAB impacts: what does the loss of ash mean for wildlife?

Alexis Grinde, Wildlife Ecologist,
Natural Resources Research Institute, University of Minnesota – Duluth

Connections

Eli Sagor, Extension Specialist,
University of Minnesota, Cloquet Forestry Center

The macroecology of historical insect invasions

Sandy Liebhold, Research Entomologist
USDA Forest Service

Beyond Buzz - How to harness the new media environment to conserve the actual environment

Andrew Revkin, Director of the Initiative on Communication Innovation and Impact,
The Earth Institute, Columbia University

CONCURRENT SESSION 1

A – Using big data to answer big questions in forest entomology

Moderators: Angela Mech[a], Ashley Schulz[b], and Ruth Hufbauer
[a] University of Maine
[b] Colorado State University

Availability and accumulation of data over the last few decades has allowed us to reexamine many unanswered questions, with large datasets being at the core of many multifaceted projects that have furthered the field of forest entomology. Our symposium will highlight some of the diverse uses of large data that have helped answer questions about predicting, monitoring, understanding, and controlling forest pests, and how these answers can be used to promote action that will keep our forests healthy.

Towards machine-assisted classification of bulk invertebrate specimens

Jarrett Blair[a], Michael D. Weiser[b], Michael E. Kaspari[b], Cameron D. Siler[b,c], and Katie E. Marshall[a]
[a] Department of Zoology, University of British Columbia, Vancouver, Canada
[b] Department of Biology, University of Oklahoma, Norman, OK
[c] Sam Noble Oklahoma Museum of Natural History, University of Oklahoma, Norman, OK

Abstract

Insect populations are rapidly changing, and monitoring these changes is essential for understanding the causes and consequences of these shifts. However, large scale monitoring of insect populations often involves sorting and counting many thousands of specimens, which can be labour intensive, time consuming and costly. A potential solution to this problem is automated specimen photo identification using machine learning, as it has been shown that machine learning can be used to quickly and accurately identify insects from photos (Mayo and Watson 2007, Ding and Taylor 2016, Marques et al. 2018). In this study, we train and test machine learning algorithms to classify bulk terrestrial invertebrate specimens from image data. All specimens were collected in pitfall traps by the National Ecological Observatory Network (NEON) at 27 locations across the United States. Image data was extracted as feature vectors using ImageJ.

As a case study to evaluate the feasibility of using machine learning to classify NEON's specimens, we first trained the model to classify 25 species of ground beetles (Family, Carabidae) (Figure 1; Blair et al. 2020). In this case study, species-level accuracy of our best performing model was 84.6%, with accuracy increasing as taxonomic resolution decreased. Species-level accuracy was further increased to >95% when classifications were limited to known local species pools. These results encouraged us to apply these methods to the rest of the NEON invertebrate bycatch. When simply using morphometric image data, invertebrate classification only reached an accuracy of 63%. However, when the models were also provided with contextual metadata (i.e., location, time, temperature, precipitation), classification improved to 74%.

Going forward, we will introduce extracellular DNA metabarcoding data to the machine learning pipeline to improve classification accuracy and specificity. DNA metabarcoding and

computer vision techniques have the potential to complement each other very well, as metabarcoding is useful for specific presence/absence data, but struggles with abundance, while computer vision excels at collecting morphometric and abundance data but is weaker at determining presence/absence. Overall, we present a methodological framework for non-destructively identifying bulk insect specimens collected from pitfall traps using machine learning that is neither data nor compute intensive. We recommend that machine learning identification methods such as ours be used as a tool to assist taxonomists with routine identifications rather than a complete replacement for human identification.

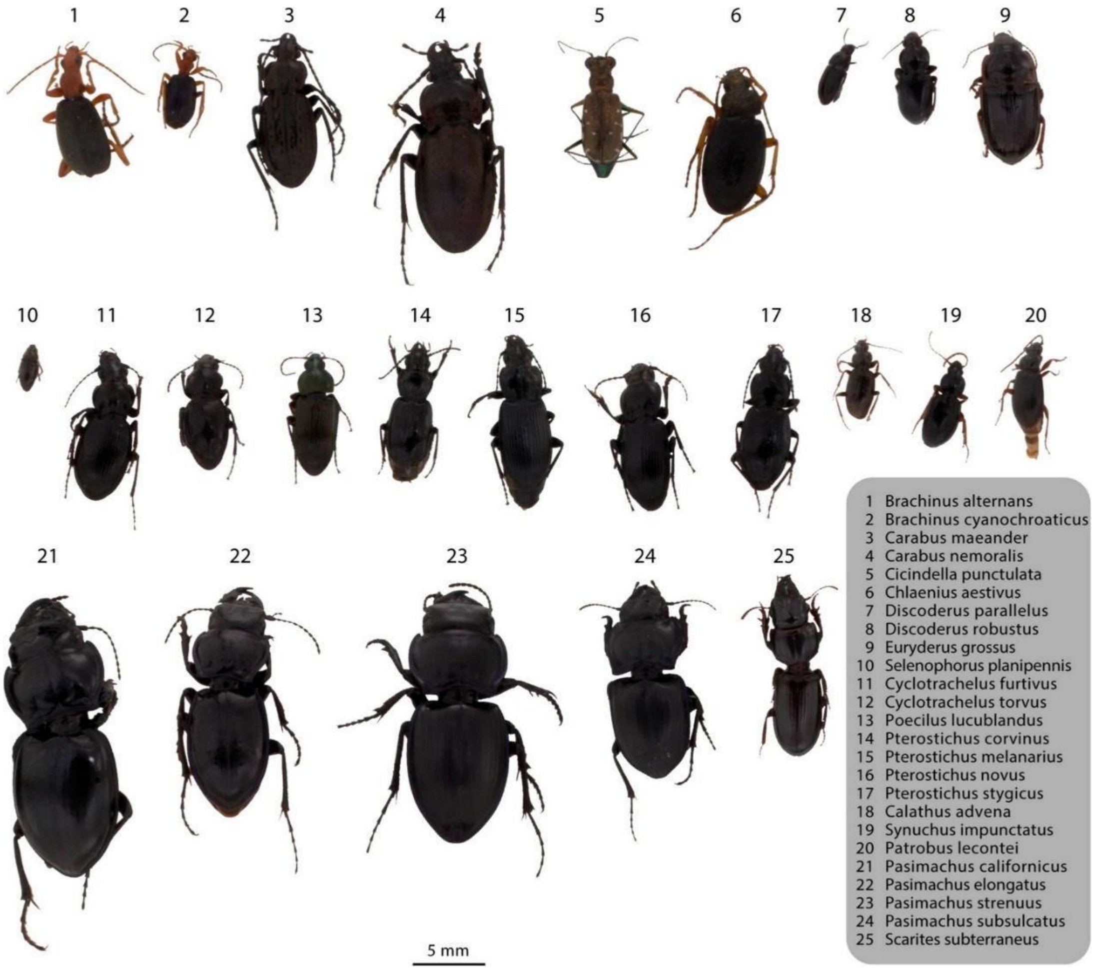

Figure 1. Collage of photographs of all Carabidae species used in the training dataset (n = 25). Specimens were cropped from their original photographs, and the background was removed. Relative scale of each specimen is conserved. Taken from Blair et al. (2020).

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Genetic and environmental factors influencing pine host quality in the mountain pine beetle outbreak: *A view through the lens of big data*

Janice Cooke[a], Catherine Cullingham[b], Rhiannon Peery[a], Joshua Miller[a], Colleen Fortier[a], Elizabeth Mahon[a,e], Marion Mayerhofer[a], Adriana Arango-Velez[a,f], Miranda Meents[a,g], Louisa Normington[a], Staffan Lindgren[c], Dezene Huber[c], L. Irina Zaharia[d], David Coltman[a,h]
[a] Department of Biological Sciences, University of Alberta, Edmonton AB, Canada
[b] Department of Biology, Carleton University, Ottawa ON, Canada
[c] Department of Ecosystem Science and Management, University of Northern British Columbia, Prince George BC, Canada
[d] National Research Council of Canada, Saskatoon SK, Canada
[e] Present address: Department of Wood Science, Faculty of Forestry, University of British Columbia, Vancouver BC, Canada
[f] Present address: GreenLight Biosciences, Research Triangle, NC USA
[g] Present address: Department of Biological Sciences, Simon Fraser University, Burnaby BC, Canada
[h] Present address: Department of Biology, Western University, London ON, Canada

Abstract

Mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins, Coleoptera: Curculionidae: Scolytinae) has caused more forest losses in Canada than any other forest insect pest species over the past 30 years (Natural Resources Canada, 2019). Characteristic of eruptive forest insects, populations of this devastating bark beetle increase dramatically from endemic to epidemic levels depending on forest susceptibility and climatic factors. MPB is native to western North America, with a historic range extending from central British Columbia (BC) south through the pine forests of the western United States to Mexico (Man 2010, Burke et al. 2017). Since the current epidemic began in 1999, MPB has killed approximately 20 million hectares of mainly lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia*) forests in BC, Alberta, and southern Saskatchewan's Cypress Hills, together with an estimated 7 million hectares of pine forests in the western states of the US (Hart et al. 2015; Hodge et al. 2017; Natural Resources Canada, 2019). The cumulative losses in BC alone have amounted to ca. 731 million m^3 of timber, or 54% of BC's merchantable pine volume (Hodge et al. 2017). Factors linked to climate change and forest management practices have contributed to the continued unprecedented expansion of MPB beyond its historic range into novel habitats [16, 24, 25] (Kurz et al. 2008, Mitton and Ferrenberg 2012, Bleiker et al. 2019), where most active outbreaks are currently located. Over the course of the epidemic, MPB has successfully established in

more northerly, easterly and higher elevation forests than previously recorded (Bleiker et al. 2019). Most active outbreaks are currently located in Alberta. Here, lodgepole pine hybridizes with jack pine (*Pinus banksiana* Lamb.), a boreal forest species whose range stretches from Alberta to the Maritime Provinces. Lodgepole pine, jack pine and their hybrids create a complex mosaic hybrid zone covering much of northern Alberta and extending into the Northwest Territories. MBP has spread across this hybrid zone over the past number of years, and we documented host range expansion to genetically pure jack pine within this hybrid zone in 2010 (Cullingham et al. 2011). With the right combination of environmental conditions and MPB population pressures, it is conceivable that MPB could continue to spread eastward through the jack pine of the boreal forest, given that there are few if any barriers to continued eastern spread of MPB (Bleiker et al. 2019). Inadvertent human-mediated movement of MPB, such as by transport of infected firewood, could facilitate eastern spread (Bleiker et al. 2019).

Host quality is a key determinant of MPB population dynamics (Bleiker et al. 2019). Ecological and physiological research suggests that host quality is modulated by both environmental and genetic factors (Bleiker et al. 2019). Over the past several years, we have used genomic approaches to ask the following questions: (1) How do environmental factors affect host quality, particularly in novel environments? and (2) Are there genetic signatures that relate to host quality, between species or within species? In other words, is there a genetic component to host quality, or are survivors just lucky?

To address the first question, we have used transcriptome profiling to investigate the effects of water limitation and nitrogen availability on lodgepole and jack pine responses to *Grosmannia clavigera* [Robinson-Jeffrey and Davidson] Zipfel, de Beer and Wingfield, a prominent Ophiostomatoid fungal symbiont of MPB that is often used as a proxy for MPB (Adams et al. 2008, Plattner et al. 2008, Roe et al. 2011, Adams et al. 2013). Transcriptome profiling for the water limitation experiment was carried out a few years ago using microarray technology, while transcriptome profiling for the nitrogen availability experiment was carried out more recently using RNA-Seq. Mining patterns of gene expression from these transcriptome datasets allows for both hypothesis testing and hypothesis generation. In the water limitation experiment, we found that core molecular responses of lodgepole and jack pine are similar, but key differences are also apparent. Global patterns of gene expression provide evidence for water limitation-induced increases in expression of several defense-associated genes in non-inoculated seedlings, suggesting that constitutive defenses were increased under conditions of water deficit. Transcript profiles for some genes in water-limited *G. clavigera*-inoculated seedlings also showed an attenuated induction, suggesting that induced defenses were impaired under water deficit stress. Genes that showed enhanced constitutive expression were not necessarily those that showed attenuated induced expression, pointing to the advantage of globally profiling thousands of genes as a monitor for the processes that they are involved in rather than investigating single genes or single processes. These results were consistent with our previous findings (Arango-Velez et al. 2014; Arango-Velez et al. 2016). In the nitrogen availability transcriptome profiling experiment, we saw some support for nitrogen availability altering N allocation to growth versus defense. We are presently using physiological and microscopy approaches to provide additional evidence to support these observations.

To address the second question, we have used large-scale DNA genotyping of a unique genetic resource to identify genetic signatures that differentiate surviving lodgepole pine from lodgepole pine in the same stand that were attacked and ultimately killed by MPB. A common garden was established using seeds extracted from cones collected from MPB-killed killed parents and cones collected from survivor parents from four sites in northcentral BC that sustained hyperepidemic. This collection of genetic material has been described previously (Balogh et al. 2018). A total of 481 individuals were genotyped at ca. 14000 high quality single nucleotide polymorphisms (SNPs), and the resulting dataset was analyzed using a combination of quantitative and population genomic techniques. These analyses showed a high heritability for survivorship, and identified a number of candidate loci that predict survivorship. We are presently validating these models and loci with an independent data set, and investigating whether any of the loci associated with MPB resilience plays a role in host quality.

Collectively, these genomic studies have enabled us to investigate long-standing questions about host-MPB interactions in new ways, providing evidence that both environment and genetics contribute to lodgepole and jack pine host quality.

Keywords: genomics, host quality, tree defense, resilience

Acknowledgements: This research was supported by grants to J.E.K.C. from the Natural Science and Engineering Research Council of Canada (grants No. NET GP 434810-12 and STPGP 521200-18), Alberta Innovates Bio Solutions (grant No. Bio-14-009) and fRI Research (grant No. 246.33). Grant No. NET GP 434810-12 included contributions from Alberta Agriculture and Forestry; fRI Research; Manitoba Conservation and Water Stewardship; Natural Resources Canada, Canadian Forest Service, Northwest Territories Environment and Natural Resources; Ontario Ministry of Natural Resources and Forestry; Saskatchewan Ministry of Environment; West Fraser; and Weyerhaeuser. Grant No. Bio-14-009 included contributions from Alberta Agriculture and Forestry. This research was enabled by support provided by WestGrid (https://www.westgrid.ca) and Compute Canada (www.computecanada.ca). The authors would like to thank Sally Aitken (University of British Columbia), Leonard Barnhardt (Alberta Agriculture and Forestry, retired), Andy Benowitz (Alberta Agriculture and Forestry), Sophie Dang (University of Alberta), Corey Davis (University of Alberta), Jeff Dean (Mississippi State University), Rory McIntosh (Saskatchewan Environment), Lindsay Robb (Alberta Agriculture and Forestry), Fiona Ross (Manitoba Agriculture and Resource Development), Taylor Scarr (Natural Resources Canada, Canadian Forest Service), Dale Simpson (Natural Resources Canada, Canadian Forest Service, retired) Ward Strong (BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, retired), and Sam Yeaman (University of Calgary) for their collaboration, partnership and assistance, as well as the many members of the Cooke Lab who have made technical contributions to this research.

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Forest integrated pest management programs in the USA with focus on the National Gypsy Moth Slow the Spread Program

Tom W. Coleman[a], Andrew D. Graves[b], Robbie Flowers[c], Robert J. Rabaglia[d], Brent Oblinger[c], James J. Jacobs[e], Bruce Moltzan[d], Travis Perkins[f], Christopher Foelker[g]
[a] USDA Forest Service, Forest Health Protection, Asheville, NC
[b] USDA Forest Service, Forest Health Protection, Albuquerque, NM
[c] USDA Forest Service, Forest Health Protection, Bend, OR
[d] USDA Forest Service, Forest Health Protection, Washington, D.C.
[e] USDA Forest Service, Forest Health Protection, St. Paul, MN
[f] Department of Entomology, Michigan State University, East Lansing, MI
[g] Wisconsin Department of Agriculture, Trade, and Consumer Protection, Madison, WI

Abstract

USDA Forest Service, Forest Health Protection (FHP) supports and funds forest integrated pest management (IPM) across all landownerships (i.e., federal, state, and private lands) in the USA. We assessed management records from 2011 to 2019 that treated approximately 6 million acres to look at forest management trends. Suppression treatment acres surpassed prevention treatment acres and the majority of treatment acres accomplished were located on cooperative lands (i.e., private and state lands). Semiochemical control, biological control, chemical control, silviculture, and physical/mechanical control strategies are the most common management activities supported by FHP with semiochemical control comprising >60% of the management work. Five taxa represent >97% of the acres accomplished during this period and FHP treats more non-native, invasive species than native species. Suppression treatments for the European gypsy moth, *Lymantria dispar dispar*, account for the majority of treatment acres since 2011 by FHP and their partners. The National Gypsy Moth Slow the Spread (STS) Program represents one of the most comprehensive and longest running forest IPM programs in the world. After 20 years, STS continues to successfully reduce the rate of spread of European gypsy moth. Since 2000, approximately 67,000 traps have been monitored annually in the program

and >9.7 million moths have been collected. The program treats a mean of approximately 442,000 acres annually and mating disruption comprises 88% of the treatments. Mean treatment success for larvicide and mating disruption treatments surpassed 81% and 91%, respectively, since the start of the program. The mean rate of spread for gypsy moth has been reduced by >80% than its historical rate of spread in the U.S. The STS program has concentrated trapping and treatment work in central and southern Wisconsin, central and southern Ohio, and western Virginia. These regions represent high priority areas for the STS program and should be the focus for future management efforts.

Synthesis and utilization of big data for forecasting the impacts of non-native forest insects in North America

Ashley N. Schulz[a], Ruth A. Hufbauer[a], Carissa F. Aoki[b], Matthew P. Ayres[c], Kamal J.K. Gandhi[d], Nathan P. Havill[e], Daniel A. Herms[f], Angela M. Hoover[g], Andrew M. Liebhold[h,i], Scott Maco[j], Travis D. Marsico[k], Kenneth F. Raffa[l], Kathryn A. Thomas[g], Patrick C. Tobin[m], Daniel R. Uden[n], Angela M. Mech[o]
[a] Colorado State University, Fort Collins, CO, USA
[b] Bates College, Lewiston, ME, USA
[c] Dartmouth College, Hanover, NH, USA
[d] University of Georgia, Athens, GA, USA
[e] USDA Forest Service, Northern Research Station, Hamden, CT, USA
[f] The Davey Tree Expert Company, Kent, OH, USA
[g] USGS Southwest Biological Science Center, Tucson, AZ, USA
[h] USDA Forest Service, Northern Research Station, Morgantown, WV, USA
[I] Czech University of Life Sciences, Suchdol, Prague, Czech Republic
[j] The Davey Tree Expert Company, Kirkland, WA, USA
[k] Arkansas State University, Jonesboro, AR, USA
[l] University of Wisconsin, Madison, WI, USA
[m] University of Washington, Seattle, WA, USA
[n] University of Nebraska, Lincoln, NE, USA
[o] University of Maine, Orono, ME, USA

Abstract

Introduced insects are increasingly invading global forest ecosystems, causing impacts that range from minor damage to functional host extinction (Aukema et al. 2010). Forecasting the probability of impact of non-native insects that have not yet arrived is essential for improving biosecurity measures (Tobin et al. 2014; Robinet et al. 2020). To forecast impact, we must first identify the mechanisms that are driving impacts. Using available data from 248 introduced insects currently established in North American forest ecosystems (Mech et al. 2020a,b), we determined impact for each insect (Schulz et al. 2020) and evaluated several drivers that could potentially explain why some introduced insects are benign while others are catastrophic (Mech et al. 2019). We considered four main submodels: (i) insect traits, (ii) host traits, (iii) native and novel host evolutionary history, and (iv) insect evolutionary history (Mech et al. 2019). We found differences between the factors that drive the impacts of insects that feed on conifers versus woody angiosperms (hereafter, hardwoods), hardwood-feeding insects that have a narrow host breadth versus those with a large host breadth, and Scolytine versus other insects that feed on a narrow range of hosts. Insect traits, such as feeding guild, seem to be significant for forecasting impact of some insects that feed on hardwoods, but not conifers. Host traits that predicted impact varied depending on host type (i.e., conifer or hardwood), with the most impacted hosts being shade tolerant and drought intolerant hosts of conifer-feeding insects and intermediate shade tolerant hosts of hardwood-feeding insects with a wide host breadth (i.e., the insect feeds on a few families of trees). We found a quadratic relationship between impact and the shortest divergence time (mya) between native and North American hosts for most conifer- and hardwood-feeding insects, except for Scolytines that fed on a narrow range of hosts, which had a linear relationship between impact and divergence time. The insect evolutionary history submodel was only included in the Scolytine model, where non-native Scolytines that had a North American relative in the same tribe had a higher impact than Scolytines without a relative in the same tribe. The significant submodels were consolidated into composite pest impact models that can be used to forecast which non-native insects have a high probability of causing tree mortality in North American forests if they become established. In total, we developed five composite pest impact models – (i) hardwood-feeding Scolytines with a narrow host breadth, (ii) hardwood-feeding non-Scolytines with a narrow host breadth, (iii) hardwood-feeding insects with a wide host breadth, (iv) conifer-feeding insects that are sapfeeders, and (v) conifer-feeding insects that are not sapfeeders – that have been built into an i-Tree Pest Predictor (iTPP) tool. After a user enters some data on an insect's taxonomy, feeding guild, native range and climate, and native host list, the iTPP tool will forecast the probability that the insect will have a high-impact on 360+ hardwood and/or 50+ conifer trees native to North America. The iTPP tool will be incorporated into i-Tree (https://www.itreetools.org/) – a software suite that quantifies forest structure, risk from forest health threats, and environmental benefits of trees – so the models are accessible and can help support decision-making by federal scientists, academics, and forest resource managers.

Keywords: biological invasions, ecological forecasting, evolutionary history, i-Tree Pest Predictor tool, non-native insects, risk assessment

Acknowledgements: We thank Dr. Jill Baron and the U.S. Geological Survey John Wesley Powell Center for Analysis and Synthesis, Fort Collins, CO, for their support of this project. We also thank David Campbell (University of Washington) and Terry Arundel (USGS) for database assistance, Karla Boyd (University of Maine), Lekeah Durden (USGS-NFS Graduate Research Intern), and Atticus Wolf (University of Arizona) for assistance with data entry, and the Digital Arts Leadership and Innovation (DALI) Lab at Dartmouth College for assisting with tool development. This project was conducted as a part of the "Predicting the next high-impact insect invasion: Elucidating traits and factors determining the risk of introduced herbivorous insects on North American native plants" working group supported by the U.S. Geological Survey John Wesley Powell Center for Analysis and Synthesis (to KAT, TDM, DAH, and PCT, and Cooperative Agreement No. G16AC00065 to PCT), U.S. Department of Agriculture Forest Service National Urban and Community Forestry Advisory Council Grant (Grant No. 19-DG-

11132544-022 to RAH, DAH, and MPA), and the U.S. Department of Agriculture Forest Service Eastern Forest Environmental Threat Assessment (Grant No. 15-JV-11242303-103 to PCT). Additional support was provided by the University of Washington, Nebraska Cooperative Fish and Wildlife Research Unit, National Science Foundation Long Term Ecological Research program (MPA), U.S. Department of Agriculture Forest Service International Programs (MPA and AML), U.S. Department of Agriculture National Institute of Food and Agriculture (Hatch project 1012868 to RAH and Hatch project ME022124 to AMM through the Maine Agricultural & Forest Experiment Station), and U.S. Geological Survey Ecosystems Mission Area to KAT and AMH. PCT acknowledges support from the David R.M. Scott Endowed Professorship in Forest Resources. Salary support and matching funds were provided by our respective institutions. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the United States Government.

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B – Invasive ambrosia beetles in North America

Moderators: Bob Rabaglia[a] and Sheri Smith[b]
[a] USDA Forest Service, Forest Health Protection, Washington, DC
[b] USDA Forest Service

Invasive ambrosia beetles have had an impact on the health of North America's urban and rural forests. In the past 30 years, there has been an increasing number of these non-native beetles and impacts. This session will discuss the species present in North America, highlight a few species having significant impacts, research to understand and manage them, and potential invaders in Asia.

Invasive ambrosia beetles in North America

Bob Rabaglia[a]
[a] USDA Forest Service, Forest Health Protection, Washington, DC

Abstract

There are nearly 70 species of non-native bark and ambrosia beetles established in North America. Several species of ambrosia beetles in the tribe xyleborini are impacting urban and rural forests in the southeastern US and California. Surveys by the USDA Forest Service and APHIS target new introductions of these species at ports and high-risk locations across the US. As introductions and establishments of new non-natives continue, it is important to understand pathways, target early detections and assess impacts of current and potential invaders across North America.

Forest insects and pathogens move around the world through trade in forest products and wood packaging materials. As global trade increases and becomes quicker, there has been increasing success in the introduction and establishment of these forest pests. Bark and ambrosia beetles (Curculionidae: Scolytinae) are the most commonly intercepted group of beetles at US port-of-entry. Worldwide, there are more than 6,000 species of Scolytinae, including more than 1,800 species of ambrosia beetles. Of the more than 560 species of bark and ambrosia beetles in the US, 75 of these are ambrosia beetles, and of those, more than 33 are non-native ambrosia beetles. Canada has a lower species diversity of scolytines and also a lower percentage of non-native species (8%). Although Mexico has a far greater number of species, it has a much lower percentage of non-natives (3%) (Table 1).

Table 1. Total and number of non-native species of Scolytinae in Canada, US, and Mexico.

	Total species	Total non-natives	Bark beetles	Seed & twig beetles	Total Ambrosia beetles
Canada	205	16 (8%)	8	0	8
Mexico	827	24 (3%)	3	16	5
USA	560	~65 (12%)	14	17	~33

The establishment of non-native bark and ambrosia beetles in North America is not a new issue. By 1900, there were five species (1 ambrosia beetle and 4 bark beetles) established in the US. However, in the past 40 years the rate of introduction and establishment has increased significantly. Between 1980 and 2020, there were 24 species of non-native ambrosia beetles and 9 species of non-native bark beetles established in the US.

Ambrosia beetles, especially those in the tribe Xyleborini, are good invaders of new areas for several reasons. They are cryptic, breeding in the xylem of wood products or dunnage, and easy to miss by inspectors. They also have a wide host range since they feed on the fungus they carry with them, so they have a ready food source as long as they can find a tree to attack. Xyleborine ambrosia beetles also have a sib-mating system. When a female leaves her brood gallery, she is usually mated, but if not, she will lay eggs, which develop into males and then will mate with them to start a new population. Finally, many of the current trading partners with North America countries have a high percentage of xyleborine ambrosia beetles native to those countries.

Many of the most injurious non-natives scolytines in North America are in the Xyleborini (Table 2). In recent years, several species have had a significant impact on forests in the US. *Xyleborus glabratus*, the vector of the fungus that causes laurel wilt (*Raffaelea lauricola*) has caused extensive mortality of red bay, and more recently sassafras in the southeastern US. In California, two species of *Euwallacea* (*fornicatus* and *kuroshio*) are killing many different tree species in both urban and natural forests. Recently, *Xyleborus monographus* has been found attacking oak trees in the Napa region of California.

During this session, there were three presentations on these four species, and a presentation on potential new, non-native xyleborines in Southeast Asia.

Table 2. Injurious non-native scolytines established in North America.

Anisandrus dispar *
Xyleborinus saxesenii *
Scolytus multistriatus
Xylosandrus compactus *
Xylosandrus crassiusculus *
Xylosandrus germanus *
Xyleborus glabratus *
Euwallacea fornicatus *
Euwallacea kuroshio *
Xyleborus monographus *

Those marked with an * are in the Xyleborini

Keywords: non-native, ambrosia beetles, scolytinae

Update on invasive ambrosia beetles in California

Sheri Smith[a] and Stacy Hishinuma[a]
[a] USDA Forest Service

The Mediterranean oak borer (MOB), *Xyleborus monographus*, is an invasive ambrosia beetle native to the Mediterranean region, including Europe, the Middle East, and North Africa, where it primarily attacks oak species. The first North American infestations of MOB were confirmed in valley oaks in Napa County, California in late 2019, followed by Lake and Sonoma Counties in early 2020, and Sacramento County in September 2020. MOB attacks at least 12 species of oaks in its native range. In California, it has been found infesting two species of white oak: most commonly valley oak and, to a lesser extent, blue oak. Several species of fungi have been found associated with MOB in Napa County, and research is underway to determine if these fungi cause tree diseases. For more information and a MOB pest alert can be found here: https://www.ucanr.edu/sites/mobpc/

In southern California, two species within the *Euwallacea fornicatus* species complex, *Euwallacea fornicatus* (polyphagous shot hole borer) and *E. kuroshio* (Kuroshio shot hole borer), have caused extensive tree mortality in urban areas. These beetles are now established in Santa Barbara, Ventura, Los Angeles, Orange, Riverside, San Bernardino, San Diego, and San Luis Obispo Counties with overlapping ranges in some counties. A statewide strategic initiative is underway to control these beetles through: 1) research and technology development; 2) survey, detection, and rapid response; 3) examining greenwaste and firewood as pathways for movement; 4) outreach and education. For more information, please visit: https://ucanr.edu/sites/pshb/

Update on red bay ambrosia beetle and laurel wilt in the southeast

Bud Mayfield[a]
[a] USDA Forest Service

The redbay ambrosia beetle (RAB), *Xyleborus glabratus*, was first detected in North America in 2002 near Savannah, GA and has since spread throughout the southeastern United States. One of its symbiont fungi, *Raffaelea lauricola*, causes a vascular disease known as laurel wilt that has killed hundreds of millions of trees in the family Lauraceae. This presentation will examine the known distribution, hosts, impacts, and management challenges associated with this insect-pathogen complex and its status as a potential threat to lauraceous plants in other regions of the world.

Xyleborine ambrosia beetles in Southeast Asia and potential new invaders

Sarah Smith[a] and Anthony Cognato[a]
[a] Michigan State University

The greatest source of introduced xyleborine ambrosia beetles is Southeast Asia. Yet prior to 2019, a review of the fauna and comprehensive identification keys were non-existent. Recently, 315 xyleborines mostly occurring in mainland Southeast Asia were reviewed in an illustrated monograph. Sixty-three new species were described, and other taxonomic changes were made. Dichotomous keys and web-based multi-entry keys were included. In addition, the foundation for a two-gene DNA identification scheme was developed for the fauna. We discuss the limits of morphological and DNA diagnostic characters, potential new invaders, and future taxonomic research.

C – Impacts of listing the monarch butterfly under the Endangered Species Act: ecology, policy, and conservation

Moderator: Rich Hofstetter[a]
[a] Northern Arizona University

Recent studies found that if current trends continue, both the western and eastern monarch populations face migratory collapse within the next 20 years. In the 1990s, the eastern population numbered nearly 1 billion butterflies, and the western population numbered more than 1.2 million. Last year's winter counts recorded fewer than 30,000 western monarchs and around 225 million eastern monarchs. Forest habitat restoration and conservation efforts may benefit or be hampered by listing the monarch under the Endangered Species Act. In this session, we discuss the politics, ecology, citizen science, and conservation of the monarch butterfly as well as its use of forest habitats and interactions with forest ecosystems.

Warranted, but precluded: what that means for monarchs and the people who care about them'

Karen S. Oberhauser[a]
[a] University of Wisconsin, Madison Arboretum, Madison, WI

In December 2020, the US Fish and Wildlife Service announced their decision that giving monarchs the protection of the Endangered Species Act (ESA) as a Threatened Species was warranted but precluded by work for species that have more pressing conservation needs. The ESA provides important protections for species and habitats, and it is likely that monarchs would have benefited from this protection. Their numbers are declining, and both the Eastern and Western Migratory Populations have reached numbers that population viability analyses suggest could lead to extinction. The decision that monarch listing is warranted means that we need to do all we can to ensure that their numbers not only stop declining, but increase.

Overview

On August 26, 2014, the Center for Biological Diversity, Center for Food Safety, Xerces Society for Invertebrate Conservation, and the late monarch expert Dr. Lincoln Brower petitioned the Secretary of the Interior, through the United States Fish and Wildlife Service (USFWS), to protect the monarch butterfly (*Danaus plexippus plexippus*) as a threatened species under the Endangered Species Act (ESA) (Center for Biological Diversity et al. 2014). On December 15, 2020, after careful deliberation and the input of hundreds of individuals and organizations, the USFWS reached the decision that adding the monarch butterfly to the list of threatened and endangered species is warranted but precluded by work on higher-priority listing actions for other species (Federal Register 2020).

Protecting species and their habitats is important

Humans depend on the ecosystem services provided by intact habitats: pollination, clean air, water filtration, extreme weather mitigation, and even our own mental and physical well-being. The loss of species indicates that the intact ecosystems required to support these services are not working properly. Additionally, many would argue that because our actions destroy ecosystems and drive species to extinction, we have a moral and ethical responsibility to protect natural systems as best we can.

Monarchs matter

The monarch is a flagship species that builds connections between people and the natural world. Monarchs are beautiful, interesting, familiar, culturally significant, and well-loved by people in diverse communities throughout North America. People care a great deal about them, and I would argue that anything that strengthens connections to nature is important. We have very little hope of saving natural systems – for the benefit of all living things, including ourselves – unless people care.

In addition to their value as a flagship species, monarchs are like the proverbial canary in the coalmine. A decline in their numbers is a signal that the natural systems that support them are not working.

Monarchs are not doing well

The year-to-year fluctuations in monarch numbers, typical of most insects, makes it difficult to be precise about how much monarch populations have declined since we started measuring them. That said, the fact that North American monarch populations are declining has been well documented (Semmens et al. 2016, Rendon-Salinas et al. 2021), with particularly steep declines for the last two decades for both the eastern (Semmens et al. 2016, Zylstra et al. in press) and western populations (Schultz et al. 2017, Pelton et al. 2019). Projection models suggest that the monarch decline is worrisome enough to predict a monarch quasi-extinction probability for the eastern population of 11-57% over the next 20 years (Semmens et al. 2016). Anyone who has observed monarchs, even casually, over the past 20 or so years in the Upper Midwestern U.S. has noticed that their numbers are lower than they used to be.

We generally measure the size of the Eastern Migratory Population (the population that migrates to Mexico) by the numbers of hectares of land with trees covered by monarchs in their Mexico wintering sites. Since we've been measuring, this number has fluctuated from a high of 18.2 hectares in the winter of 1996–97 to a low of 0.67 hectare in the winter 2013–14. For the past few years, the population has been fluctuating around an average of just under three hectares (Rendon-Salinas et al. 2021). Semens et al. (2016) estimated that a population that fluctuates around 6 hectares is likely to survive for at least 20 years. Since 2007, we have only achieved 6 hectares once, in the winter of 2018–19.

A similar population viability analysis was done for the Western Migratory Population that winters in sites along the coast of California. That analysis predicted that the population was unlikely to recover if it declined to 30,000 monarchs at these sites (Schultz et al. 2017). It reached that number in the winter of 2018–19, and was approximately the same in 2019–20. In the last count, there were fewer than 2,000 monarchs at the California wintering sites (Xerces

Society 2021). The western population may have entered what is known as an “extinction vortex” from which it will not recover. This incredibly sad development is a depressing indication that the models work.

The Endangered Species Act matters

In my opinion, the ESA is one of the most important pieces of environmental legislation in the United States. The Act, signed into law by President Richard Nixon on December 28, 1972, recognized that the species with which we coexist are of "esthetic, ecological, educational, recreational, and scientific value to our Nation and its people," and that many native plants and animals were in danger of becoming extinct. The ESA is designed to protect both species at risk of extinction *and* the ecosystems upon which they depend. Because no other U.S. law provides such sweeping protection of habitats, the work done to protect individual species has ramifications for other species. Millions of acres of critical habitat have been designated and protected.

The ultimate goal of listing a species is that it recovers to the point that it no longer needs ESA protection. Most listed species have a recovery plan with objective, measurable criteria that, when met, would result in a determination that the species can be delisted. Since the inception of the ESA, 2,360 species have been listed (1,414 animals and 946 plants), and 93 have been delisted. One might interpret this as a sign that the Act doesn’t really work, because so few have been delisted—but it is important to note that only 11 listed species have gone extinct. A recent study (Greenwald et al. 2019) estimates that the Endangered Species Act has prevented the extinction of roughly 291 species since its passage, and has saved more than 99% of species under its protection.

Summary

We need to do more to protect monarchs. Thousands of people are working to preserve monarch habitat, and I firmly believe that without these efforts monarchs would be much worse off. We can learn from the Red Queen in Lewis Carroll’s *Through the Looking Glass*, who said to Alice "Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!" Semmens et al. (2016) told us that current monarch numbers are not sustainable. If we agree that preserving this amazing species for our children and grandchildren is a worthwhile goal, we’ll need to “get somewhere else,” i.e. we must run faster. The protection of the Endangered Species Act would have helped us do that. However, while the USFWS has determined that listing monarchs is warranted by documented declines in their numbers, other species are more at risk. Now, it is up to us to speed up our efforts.

Keywords*:* monarch butterflies, Endangered Species Act, insect conservation

Acknowledgements: Thanks to Richard Hofstetter for organizing a symposium on monarchs and the Endangered Species Act at the North American Forest Insect Conference.

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Partnering to bring all hands on deck for monarch conservation

Wendy Caldwell[a]

[a] Monarch Joint Venture

While the needs of monarch butterflies seem simple - milkweeds to grow their young, nectar to sustain adult butterflies, and specific forest locations to accommodate their overwintering needs - a coordinated and robust approach stretching across North America is required to ensure the amazing monarch migration persists for generations to come. The charisma and decline of this insect icon present a unique opportunity to engage people and partners from all backgrounds in a robust conservation movement that yields benefits far beyond the monarch butterfly. Leveraging the unique strengths and resources of a network of over 100 partner organizations across the U.S., the Monarch Joint Venture (MJV) brings stakeholders together to increase the scale and effectiveness of species conservation measures. The MJV coordinates and engages its partners to design and deliver effective habitat conservation, education campaigns, and research not only to support monarch butterflies, but to promote biodiversity and broader ecosystem functions. It is only through coordination and collaboration that we can engage *All-Hands-On-Deck* to protect the monarch butterfly migration.

Adult monarch abundance is higher in burned sites than in grazed sites

Julia Leone[a], Diane L. Larson[b], Jennifer L. Larson[c], Nora Pennarola[d], and Karen Oberhauser[e]
[a] University of Minnesota, St. Paul
[b] U.S. Geological Survey, St. Paul, MN
[c] Polistes Foundation, Inc., St. Paul, MN
[d] University of Minnesota, St. Paul
[e] University of Wisconsin-Madison, UW-Madison Arboretum

Tallgrass prairie is important summer breeding habitat for monarchs (*Danaus plexippus)* and a product of climate and natural disturbances such as fire and grazing. Only ~1% of pre-European prairie remains in North America. Although current land managers often attempt to mimic historic disturbance regimes, this can be challenging in a landscape fragmented by human land use. It is essential to understand the impacts of current fire and grazing regimes on monarch butterflies so that land managers and conservationists can better protect and manage important prairie habitat.

We studied the association of adult monarch abundance with fire or cattle grazing management at 20 remnant sites in Minnesota tallgrass prairie. Monarchs were surveyed using a modified Pollard Walk six times at each site during 2016 and 2017. We measured *Asclepias* spp. (milkweeds, monarch host plants), forb frequency, and area of each site; percent prairie was measured in a 1.5 km buffer area surrounding each site.

Monarch abundance was nearly three times higher at sites managed with fire than grazing. Within grazed sites, monarch abundance was inversely related to cattle stocking rates, which suggests that heavy grazing may negatively impact monarchs. Milkweed and forb frequency did not differ between burned and grazed sites and were not associated with monarch abundance. We present opportunities for future research to help elucidate mechanisms behind the patterns we observed.

Historical monarch overwintering colonies in central Mexico, 1976–1991

Wayne E. Thogmartin[a], Erin R. Zylstra[b], M. Isabel Ramírez[c], and Elise F. Zipkin[b]
[a] U.S. Geological Survey, Upper Midwest Environmental Sciences Center
[b] Michigan State University
[c] Universidad Nacional Autonoma de Mexico

Systematic monitoring of overwinter colony size in Mexico since the early 1990s suggests the eastern migratory population of monarch butterflies has declined by approximately 80%. There are some scholars, however, that question whether monarch butterflies have declined at all. Recently, a number of scholars arrayed literature-derived values of overwinter abundance prior to the initiation of systematic monitoring in Mexico that, in concert with recent monitoring, suggest to them that the eastern migratory population of monarch butterflies has not appreciably declined. We examined these same data and found that 30-40% of the colonies were unmeasured in these early years prior to initiation of systematic monitoring. Thus, when these omissions are addressed, more reasonable estimation of past abundance suggests that monarch butterfly populations were likely considerably higher. The possibility exists that monarchs were as much as twice as abundant in the late 1970s as they were when systematic monitoring began in the late 1990s. Thus, when these literature-derived values are properly examined, we find that the recent period of decline is substantiated and, in fact, is likely preceded by a period of decline beginning at least as far back as 1978.

For more on this topic, see Zylstra, E.R., Thogmartin, W.E., Ramírez, M.I., and Zipkin, E.F., 2020, Summary of available data from the monarch overwintering colonies in central Mexico, 1976–1991: U.S. Geological Survey Open-File Report 2020–1150, 10 p., https://doi.org/ 10.3133/ ofr20201150.

Southwest milkweeds and their use by Monarchs

Mike Wagner[a], Richard Hofstetter[a,b,*], Casey Hensen[a], and Danielle Stroh[a]
[a] AZ Milkweeds for Monarch
[b] School of Forestry, Northern Arizona University, Flagstaff, AZ, USA
[*] Presenter

The Southwest contains an extraordinary abundance of milkweed species representing half of the milkweed species in the US. Arizona alone contains 41 species (USDA distribution website, Nabhan et al. (2015), including desserts intersecting in Arizona) and is second only to Texas in milkweed diversity. The elevational gradient, diverse ecotones, and high elevation (reaching >8000 ft.) habitat in Arizona make it an ideal location to focus on milkweed species and ecotypes for habitat restoration and monarch usage of specific milkweed species. The locations and quality of existing monarch breeding sites, and the use of milkweed, nectar and pollen plants for either monarch caterpillar development or nectar/ pollen plant sources for pollinators are generally unknown.

Our non-profit organization, ‘AZ Milkweeds for Monarchs’ (AZMFM) is a newly formed Arizona 501c3 Nonprofit Corporation that has capacity and expertise to address these unknowns and to grow thousands of plants for monarch habitat establishment. In 2020-2021, AZMFM performed three projects to: (1) evaluate growth rate and survival of milkweed species across three elevations (7000, 5000, and 3000 ft), (2) evaluate monarch oviposition preference on various milkweed species in Arizona, and (3) evaluate soil amendments to improve milkweed species germination and growth.

We measured the growth rate and survival in natural gardens of the following milkweed species at three elevations: *Asclepius angustifolia, asperula, curassavica, fascicularis, incarnata, latifolia, linaria, speciosa, subverticillata* and *tuberosa.* We found that growth rate and survival of milkweed species varied significantly by species and elevation. Species that survived best at low elevation (3000 ft) were *angustifolia, latifolia, linaria,* and *subverticillata*; all other species survived but had survival rates less than 70%. Species that survived and grew well at the highest elevation (7000 ft) were *fasciclaris, incarnata,* and *speciosa*. *Asperula* and *incarnata* performed best at mid-elevation (5000 ft).

We performed a monarch oviposition study in two large plexiglass structures that contained three replicates of multiple milkweed species. The test was performed with 5 mated female monarchs, each test separated with unique sets of plants. Monarch oviposition preference varied greatly across milkweed species but the most preferred host was *A. angustifolia* compared to *A. subverticillata, asperula, erosa, latifolia, fascicularis* and *specioa.* The second preferred oviposition host in our study was *erosa*. Oviposition preference also matched caterpillar performance. Performance was determined by growth rate (caterpillar size and head capsule width), pupae size, and survival to adulthood.

We evaluated alternative cultural practices for a full range of AZ milkweed species and some non-native milkweed species to determine the best cultural practices for greenhouse production of high-quality planting material. We tested 11 milkweed species/provenances to ascertain the best growing media/fertilizer treatment for each species (using SC-10s). We tested the following soil treatments:

1) Cornell mix 33% each of perilite, vermiculite, peat moss with Osmocote Plus fertilizer ((15-5-8) N-P-K plus micronutrients, 3-4 month release)
2) Cornell mix with no fertilizer treatment
3) Low OM Cornell with 33% each of perilite, vermiculite and mineral soil with Osmocote Plus fertilizer. Mineral soil from Baldwin Ranch-MRW
4) Quick drain cactus mix with 50% pumice, 25 % coarse sand, 25% peat moss with Osmocote Plus fertilizer. Pumice available from Peaceful Valley (groworganic.com)
5) Cornell mix plus rock phosphate (0-3-0)
6) Cornell mix plus blue form (38-0-0)
7) Cornell mix plus Osmocote Plus fertilizer and Biochar (Humic Acid granular Peaceful Valley).

Criteria for selecting amendments include: 1) suitable formulation for mixing in potting soil, 2) gradual release formula, and 3) that the source is a reliable long-term provider. We tested the following milkweed species: *Asclepias angustifolia, asperula, currasivica, incarnata, latifolia, fascicularis, speciosa, tuberosa, subverticillata,* and *verticillate*.

Species grew significantly better with the addition of Osmocote Plus. The addition of biochar or mineral soil did not improve growth rates. Species also performed well using the cactus mix but were more sensitive to soil moisture levels and desiccated quicker if not watered. Plants performed well to blue form (38-0-0) especially verticillate but some species *(currasivica, angustifolia,* and *incarnata*) had significantly lower growth rates than plants grown with

Osmocote Plus. In general, we found that soil amendments such as Osmocote significantly improved plant performance, while soil type did not affect growth. Interestingly, *latifolia* and *asperula* were not significantly affected by soil type or soil amendments compared to other species tested.

In conclusion, milkweed species survival and growth varied across elevation/location and thus it is important to plant the correct species and provenance/genotype for each location. For conservation, we need to plant the best species and genotypes to ensure that plants survive and continue to produce seed. Not all milkweeds are used or preferred by monarch caterpillars. Of the species we tested, *A. angustifolia* is the best choice although other species (such as *erosa*) can support caterpillars. When growing milkweed for production, soil amendments are important and soil type is less important than type of fertilizer (e.g., Osmocote Plus). Some species need P and K, while others only needed N to improve growth.

Keywords: monarch, milkweed, soil amendment, *Asclepias*, performance

Acknowledgments: Thanks to Yavapai and Coconino Master Gardeners, Highlands Center for Natural History, Desert Botanical Garden, Boyce Thompson Arboretum, Arboretum at Flagstaff, NAU greenhouse, and the Sedona Rotary Club of America.

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The critical roles of the Texas corridor for eastern monarch migration

Bob Coulson[a] and James L. Tracy[a]
[a] Knowledge Engineering Laboratory, Department of Entomology, Texas A&M University

Causes for the decline in the eastern migratory monarch butterfly (*Danaus plexippus*) populations are a prominent issue in the research agenda for this iconic species. The migratory corridors in Texas play multiple and contrasting roles in the success or failure of the spring migration of monarchs out of the overwintering sites in the Oyamel fir forests of central Mexico and in the return of the fall migration to these sites. Although the general migration phenomena for monarchs has been observed for many years, the detailed boundaries for the fall and spring migratory pathways had not been defined, but are critical to evaluating mortality agents affecting reproductive success and movement. Accordingly, we defined the dimensions of the spring migration pathway by modeling the distribution of four prominent milkweed species utilized as habitat for larval monarchs and prominent species of spring flowering plants used as nectar sources for adults. We defined the dimensions of the fall migration pathway by modeling the distribution of roosting sites, as well as the fall flowering plants used as nectar to fuel the return migration. Both exercises resulted in spatially explicit boundaries for central and costal pathways of the corridor through Texas. Texas roadways play a critical role in the successful spring and fall migrations of the eastern monarch butterfly population. Between 2016 and 2021, we conducted state-wide surveys to monitor spring and fall movement of monarch. We identified perennial hotspots for fall monarch butterfly roadkill in Texas, where roadkill can comprise up to 2.5% of the Mexican overwintering population. Spring and fall roadside milkweed and monarch-preferred nectar plant hotspots were also identified which provide critical monarch resources in terms of both milkweed larval food and nectar for adults.

D – Open Session

Moderator: Nathan Havill[a]
[a] USDA Forest Service, NRS

Healthy Trees, Healthy Cities

Michelle Johnson[a], Rich Hallett[b], Rachel Holmes[c], and Chuck Bargeron[d]
[a] USDA Forest Service, Northern Research Station, Bayside, NY, USA
[b] USDA Forest Service, Northern Research Station, Durham, NH, USA
[c] The Nature Conservancy, Clifton, NJ, USA
[d] University of Georgia, Center for Invasive Species and Ecosystem Health, Tifton, GA, USA

New tree-killing insects and diseases are often spotted first in cities, making tree health monitoring a priority not only for these trees themselves, but for the health of the entire North American forest ecosystem. Seven years ago, The Nature Conservancy, USDA Forest Service, and University of Georgia partnered on the development of a scientifically rigorous, non-stressor specific tree health monitoring protocol called Healthy Trees, Healthy Cities. The protocol is non-stressor specific making it a critical tool for the early detection of new, unknown insects or diseases. Furthermore, the protocol and an associated smart phone application (app) and web-based “dashboard” leverage the expertise of civic scientists and professionals alike, increasing public awareness of tree health issues. Learn about the methodology, new tools and updated training resources, as well as examples of where these tools have been used to improve tree health efforts in cities.

Balsam woolly adelgid mortality patterns in Idaho: from invasion to long-term establishment

Gina Davis[a], Laura Lowrey[b], Tom Eckberg[c], and Jeffrey A. Hicke[d]
[a] USDA Forest Service, Forest Health Protection, Coeur d’Alene, ID, USA
[b] USDA Forest Service, Forest Health Protection, Medford, OR, USA
[c] Idaho Department of Lands, Coeur d’Alene, ID, USA
[d] University of Idaho, Department of Geography, Moscow, ID, USA

More than 110 years after first reported in Brunswick, Maine the non-native balsam woolly adelgid, BWA (*Adelges piceae*), continues to be a significant pest of true fir (*Abies*) species in eastern and western North America. Over the decades, reports of BWA-caused damage demonstrated that the intensity and extent of tree mortality varied temporally, spatially, and among host species. Further investigation into stand-level mortality patterns occurred during two separate monitoring efforts in Idaho where BWA-caused mortality rates were estimated following the discovery of BWA in the state (1986-2004) and after it was well established in most of the state (2008-2018). Observations from these two monitoring efforts are synthesized and address two key question; should forest managers expect similar stand-level mortality of true fir forests from BWA into the future; and if so, how much time do they have for mitigating losses once BWA infestations are evident?

Stand structure and climate influences on balsam woolly adelgid damage in Idaho: A statistical analysis of field measurements

Jeffrey A. Hicke[a], Gina Davis[b], Ekaterina Smirnova[c], Leonid Kalachev[d], Laura Lowrey[e], and Tom Eckberg[f]
[a] University of Idaho, Department of Geography, Moscow, ID, USA
[b] USDA Forest Service, Forest Health Protection, Coeur d'Alene, ID, USA
[c] Virginia Commonwealth University, Department of Biostatistics, Richmond, VA, USA
[d] University of Montana, Department of Mathematical Sciences, Missoula, MT, USA
[e] USDA Forest Service, Forest Health Protection, Medford, OR, USA
[f] Idaho Department of Lands, Coeur d'Alene, ID, USA

Balsam woolly adelgid (BWA) is an invasive insect in the western United States, attacking subalpine firs (*Abies lasiocarpa*) and grand firs (*Abies grandis*). Little is known about the stand structure and climate conditions favorable for BWA in these forests. In 2018, tree and insect characteristics at 28 sites in Idaho were measured for the third time; previous measurements occurred 5 and 10 years before. Here our objective was to identify stand and climate variables leading to BWA damage and tree mortality. We used generalized additive modeling, which allows nonlinear relationships between the response and explanatory variables. We modeled the proportion of host trees associated with BWA infestation. We considered multiple explanatory variables grouped by process (insect pressure, stand structure, host species and size preferences, temperature, and precipitation) to avoid multicollinearity issues. We used a modified forward selection process and considered AIC and cross-validation. The top model included insect pressure (proportion of live host species basal area with BWA present five years ago) as the most important variable. Basal area (BA) of host species 10 years ago, growing season precipitation, and water-year mean temperature were also included. The BWA response variable linearly increased with increasing insect pressure, increased roughly linearly with increasing host BA, decreased with increasing temperature, and had a humped-shaped relationship with precipitation in which the highest BWA damage occurred at intermediate values. Our results inform forest managers about the stand and climate conditions that make subalpine and grant fir stands susceptible to balsam woolly adelgid.

Azadirachtin for the control of EAB

Rhoda deJonge[a], Breanne Aflague[b], and Jeff Garnas[b]
[a] Lallemand Plant Care, Sault Ste. Marie, ON, Canada
[b] The University of New Hampshire, Durham, NH, USA

Insects respond to different systemic insecticides in different ways. Here we explain the unique mode-of-action of azadirachtin-based insecticides and review recent studies that use this active ingredient to control the invasive emerald ash borer (EAB).

What is Azadirachtin?

- Azadirachtin is a plant-based active ingredient used in number of organic insecticides on the market.

Controlling insects as a growth regulator:

- It controls insect pests by working within the insect-specific hormonal pathways, preventing molting, as well as limiting feeding and fecundity.

Highly effective control of EAB during peak invasion, and over the long term:

- Our long-range study reviews survivorship of azadirachtin-treated ash trees after ~10 years of EAB management. Injected trees have healthy canopies and a survivorship rate of ~74%.
- In our recent study with the University of New Hampshire we show that azadirachtin-based insecticides provide excellent control of EAB larvae in a New England woodlot during peak EAB
- *"(Azadirachtin-based insecticides) killed emerald ash borer larvae more quickly than the neonicotinoids"* (Poland et al., 2016 – Journal of Economic Entomology).

Asian Giant Hornet Program Update

Karen Ripley[a] and Cassie Cichorz[b]
[a] USDA Forest Service, Region 6, State and Private Forestry, Portland, OR
[b] Washington State Dept of Agriculture, Olympia, WA

The Asian giant hornet (*Vespa manadarinia*) (AGH) was first detected in British Columbia and Washington in 2019. A video overview with information about AGH including its biology, range, and potential impacts and the 2020 response from WSDA was shared. 2020 accomplishments included 6 confirmed sightings in White Rock and Aldergrove, British Columbia (after a nest was detected and successfully eradicated in Nanaimo in 2019) and 31 confirmed sightings in Whatcom County, Washington based on heavy publicity and over 2400 traps placed by WSDA, its partners and the public. One AGH nest containing 196 individuals including 75 new queens was detected in a hollow tree and was eradicated. The WSDA's trapping plans for 2021 were described. Some taxonomic references for identifying Hymenopteran groups, including *Vespa mandarinia* and its close relatives, were shared. Titles and links to these materials can be obtained from karen.ripley@usda.gov.

What is an adelgid, anyway? Species delimitation and invasion history in Adelgidae

Nathan P. Havill[a]
[a] USDA Forest Service, Northern Research Station, Hamden, CT

Several adelgid species are high-impact invasive pests in forests and tree plantations in North America and Europe. Adelgid taxonomy is notoriously unstable due, in part, to their complex polymorphic life cycles that complicate morphological species delimitation. Genetic studies to inform adelgid systematics and population genetics can help us better understand their biology and inform pest management. I will discuss recent progress towards understanding the biogeographic history of adelgids using genetic data, focusing on hemlock woolly adelgid, balsam woolly adelgid, and pine adelgids (*Pineus* spp.). It is common for adelgid species complexes to be in the midst of transition between a holocyclic life cycle (with host alternation and a sexual generation) and an anholocyclic life cycle (with no host alternation and only asexual generations). This pattern has implications for their taxonomy, pest impact, and invasion history.

CONCURRENT SESSION 2

A – Managing bark beetles during a period of rapid environmental and socioeconomic change

Moderators: Chris Asaro[a], John Nowak[a], and Chris Fettig[b]
[a] USDA Forest Service, Forest Health Protection
[b] USDA Forest Service, PSW Research Station

The rapid pace of environmental and socioeconomic change poses considerable challenges to forest managers throughout North America. The goal of this 2-hr workshop is to explore relevant issues to the management of bark beetles within the broader social, political, and biophysical environment. Changes in the frequency and severity of other disturbance regimes and stressors, forest ownership and land use patterns, and market forces will be discussed for each of five regions. Speakers will address how these factors influence management considerations today, and more importantly how anticipated changes will likely influence management considerations and bark beetle impacts in the future.

Bark beetles in the northeastern US: Managing new arrivals and monitoring others

Kevin J. Dodds[a]
[a] USDA Forest Service, Eastern Region, Forest Health Protection Durham, NH

Changing climates are modifying the interactions between bark beetles and forests in the northeastern US. While species like *Dendroctonus rufipennis* and *Dendroctonus simplex*, as well as multiple species of *Ips* are present in the region, outbreaks of these beetles have been rare. Forest managers in the northeast rarely have had to consider bark beetles and their potential impacts when developing management plans. However, the climate driven range expansion of *Dendroctonus frontalis* into New York and southern New England has changed this and put relatively large areas of unmanaged pitch pine barrens at risk (Lesk et al. 2017, Dodds et al. 2018). Since detection in 2014, suppression efforts using cut-and-leave have been undertaken on Long Island. Initiating an IPM plan for *D. frontalis* has been challenging due to complex land ownership, resistance to forest management, concern for increasing fire hazard, and lack of markets for infested trees on Long Island.

In addition to climate driven range expansions, the potential for more severe storms and periods of severe drought are predicted for the northeastern US. Large windstorms can provide easily exploitable habitat that many wood-inhabiting insects can colonize (Bouget and Duelli 2004, Gandhi et al. 2009, Wermelinger et al. 2017). While most of the insects colonizing stressed or recently killed tree material are typically innocuous in northeastern forests, increased storms may provide opportunities for damaging insect populations to develop in this material. Specifically, bark beetle species that can transition into primary tree killers, such as *Dendroctonus* spp. and *Ips* spp. are a concern after forest disturbances. Recent assessments, however, have documented a range of bark beetle responses to these disturbances with no evidence of damaging populations developing in downed material and moving into living trees (Dodds et al. 2019).

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Multi-faceted forest health and socio-economic threats from catastrophic wind disturbances in the southeastern U.S. forests

Kamal J.K. Gandhi[a], Brittany F. Barnes[a], Crystal Bishop[a], Christine Fortuin[a], Benjamin Gochnour[a], Robert Hoyt[b], Kier D. Klepzig[c], Elizabeth McCarty[a], Chelsea Miller[a], Cristian Montes[a], Thomas N. Sheehan[c], Seth Spinner[a], Caterina Villari[a], and J.T. Vogt[d]

[a] D.B. Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA
[b] Terry College of Business, University of Georgia, Athens, GA
[c] The Jones Center at Ichauway, Newton, GA
[d] USDA Forest Service, Southern Research Station, Athens, GA

Abstract

Catastrophic wind disturbances such as hurricanes and tornados are significant agents of change in the southeastern U.S. forests. Such windstorms can drastically alter forest composition and structure with positive implications for the population levels of bark beetles (due to increased woody debris), and negative for many other biotic elements. Reduction of fuel loads and forest regeneration practices after windstorms may further create compounded disturbances and economic stress on landowners and managers of pine stands. Hence, there is a great need to mitigate storm risks and to develop best management practices for these disturbed landscapes. We recently formed the National Catastrophic Wind Disturbance (NCWD)

Working Group to focus on the many cascading ecological and socio-economic impacts of catastrophic wind disturbances. Our research questions are as follows:

1) How bark beetles and their associates may respond to varying levels of wind disturbances in pine-dominated southern forests;
2) Whether post-disturbance activities may lower bark beetle populations below economic thresholds; and
3) Can we create risk assessment of which sites and stand attributes may lend to the greatest damage susceptibility, and the trickle-down effects on the economics (e.g., insurance and taxation) of managing these forests?

Results from these various projects will assist with sustainable forest management and restoration activities under continued high impacts from catastrophic wind disturbances especially under global climatic changes in the southeastern U.S.

Bark beetles are eating the West: Changing environmental and socioeconomic influences

Christopher J. Fettig[a]
[a] Pacific Southwest Research Station, USDA Forest Service, Davis, CA

Abstract

Bark beetles are important disturbance agents in conifer forests in the western United States (Figure 1). Each bark beetle species exhibits unique host preferences, life history traits and impacts, but many show preference for colonizing large-diameter trees growing in high-density stands with a high percentage of host type (Fettig et al. 2007). Tree mortality attributed to bark beetles influences the function, structure and composition of forests by regulating aspects of primary production, nutrient cycling, ecological succession, and the size, distribution and abundance of trees. At endemic populations, bark beetles often create small gaps in the forest canopy by killing individual trees or small groups of trees stressed by age, drought, defoliation or other factors. In this context, few impacts are observed. This differs from the impacts associated with outbreaks, which may negatively affect many ecosystem goods and services including timber and fiber production, water quality, fish and wildlife populations, recreation, grazing capacity, biodiversity, endangered species, carbon sequestration and storage, and cultural resources (Morris et al. 2017, 2018).

Several recent outbreaks of bark beetles in the western United States are among the largest in recorded history (Fettig et al. 2021). In this presentation, I discuss the causes of these outbreaks, impacts to ecosystem goods and services, management options, and barriers limiting our adaptive capacity to effectively address outbreaks at meaningful scales (Cottrell et al. 2020). Solutions include increasing the pace and scale of treatments (including both direct and indirect control, Fettig and Hilszczański 2015); facilitating legislative and administrative reforms that act as barriers to project implementation; rebuilding the forest products industry; developing and utilizing conservation investments; reducing the rate of atmospheric warming; and monitoring and adaptive management. Of note, natural resource managers will be increasingly challenged to manage bark beetle populations; to maintain resilient and productive

forests; and to facilitate recovery of landscapes impacted by bark beetles, other disturbances and their interactions in the western United States.

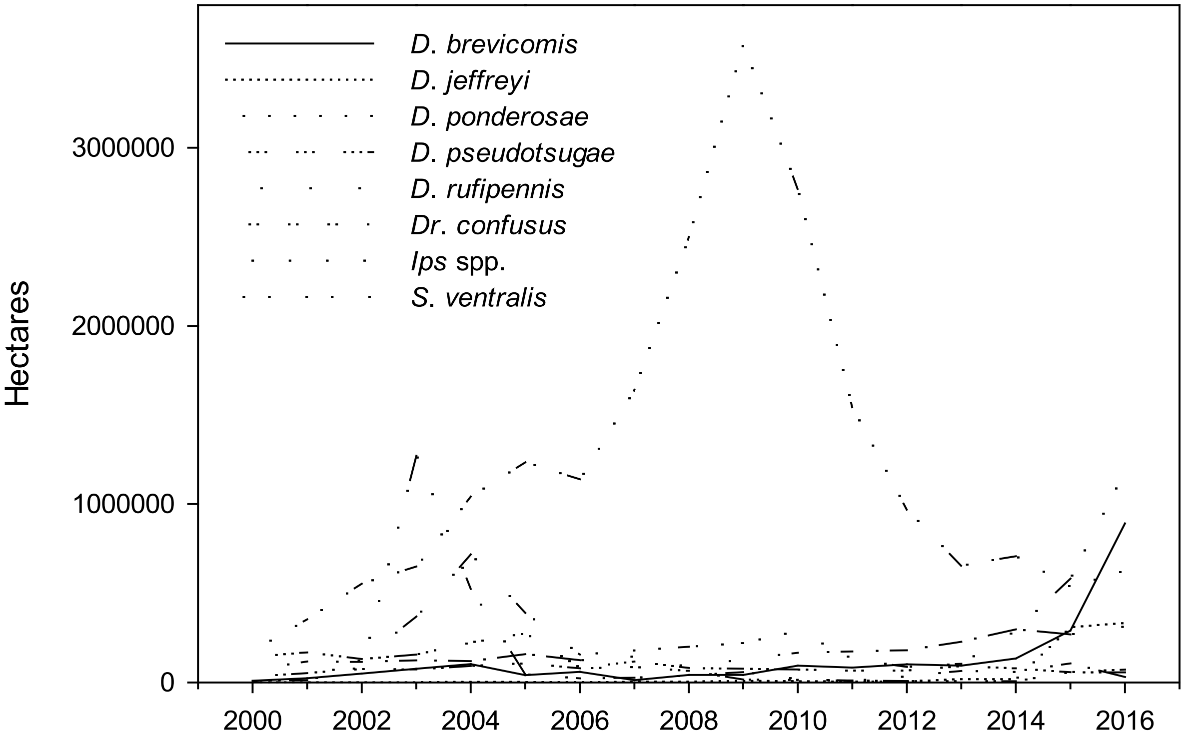

Figure 1. Area affected by conifer bark beetles in the western United States, 2000–2016. Values represent the impact observed each individual year and should not be summed across years (i.e., there may be overlap in areas affected from year to year). Data are from the U.S. Forest Service National Insect and Disease Survey database; adapted from Fettig et al. (2021).

Keywords: adaptive capacity, *Dendroctonus*, *Ips*, *Scolytus*, tree mortality

Acknowledgements: I thank the numerous colleagues who contributed to the research efforts discussed in this presentation.

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Bark beetles in British Columbia

Jeanne Robert[a]

[a] RMOM-Resource Management, Omineca, British Columbia, Canada

In British Columbia, we have been on the front lines of “rapid pace of environmental and socioeconomic change” manifesting as unprecedented bark beetle outbreaks. Bark beetles are common forest pests that are well adapted to cold northern winters across Canada. This insect normally attacks dead or weakened host trees and historical outbreaks are an integral part of forest ecosystem function. Recent weather patterns, including warm springs, dry summers, warm winters and windstorms have contributed to major bark beetle outbreaks within the last 30 years. The objective of this analysis to explore trends in bark beetle outbreaks across British Columbia, predominantly within the last 15 years. I have reviewed and compiled the provincial aerial overview forest health survey data in BC for the four major bark beetles including the most recent spruce beetle outbreak in the Omineca Region. All four major bark beetles are showing large increase in affected area in recent decades. Climate change and bark beetle damage are affecting timber supply, most obviously for lodgepole pine. Spruce, subalpine fir, and Douglas-fir timber supply may be affected within the foreseeable future. I would like to acknowledge the Government of BC forest health team for data generation and support.

Government of BC. Aerial Overview Survey: https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-health/aerial-overview-surveys/data-files

Managing bark beetles during a period of rapid environmental and socioeconomic change

Jason E. Moan[a]

[a] Alaska DNR Division of Forestry

Abstract

Alaska's size, comparatively limited infrastructure, and geographic and environmental variability pose unique challenges to bark beetle mitigation. The state's 129 million acres of forest land is comprised of temperate rainforest and boreal forest, both with a suite of associated disturbance factors including wildland fire, bark beetle and defoliator outbreaks, and wind, among others. Additionally, climate change related impacts are already being observed across the state and are expected to continue (Hennon et. al. 2016, Wolken et al. 2011). Alaska is warming faster than any other US state and at a rate twice the global average (Markon et al. 2018).

Spruce beetle (*Dendroctonus rufipennis*) is the primary bark beetle of concern across the state and occurs throughout Alaska's spruce forests. Outbreaks of spruce beetle can occur in all regions of Alaska but have largely been concentrated in Southcentral Alaska (Holsten 1990). Outbreaks are infrequent in Interior Alaska, where beetle populations are thought to generally be limited by the winter temperatures in that region (Miller and Werner 1987). Spruce beetle activity in Southeast Alaska, where the bulk of the state's harvested timber volume originates, has the potential to affect large volumes of timber even if the overall level of activity is low or moderate.

Though much of the harvested timber volume comes from Southeast Alaska, harvest volumes have been declining in the region. Additionally, between 2005 and 2015, the harvest volumes statewide decreased by half (Marcille et al. 2017a). In much of the state, processing facilities are limited. When coupled with a limited road system, large-scale management of bark beetles can be a considerable challenge. This has been illustrated in Southcentral Alaska where an ongoing spruce beetle outbreak has impacted at least 1.1 million acres since it was first detected in 2016. The area being impacted by the outbreak is also home to more than half of Alaska's population, adding additional complexity and considerations to managing the outbreak and the expanse of dead trees left in its wake.

Keywords: Alaska, spruce beetle, climate

Acknowledgements: Many thanks to A. List, H. Rinke, M. Schoofs, E. Graham, and several other Alaska DNR Division of Forestry and USDA Forest Service Forest Health Protection personnel.

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B – Domestic invasive species: curtailing the threats in our own backyard

Moderators: Robert C. Venette[a] and Andrew D. Graves[b]
[a] USDA Forest Service, NRS
[b] USDA Forest Service - R3 Forest Health Protection

The concomitant movement of wood and insects within (and across) national borders creates opportunities for the introduction of invasive pests. A common misperception is that invasive pests must come from overseas. This session begins with select cases that illustrate the severe impacts that can occur when forest pests are moved to naïve ecosystems that are still within national borders. We apply a simple framework to assess how risks associated with these species might differ within a country. Lastly, we discuss potential management options that would not necessarily require federal regulatory action but could mitigate these risks.

Heading west: *Ips grandicolis* is on the move

Brian H. Aukema[a], Derek W. Rosenberger[b], Erika L. Eidson[c], Carl L. Jorgensen[d], and Kevin D. Chase[e]
[a] Department of Entomology, University of Minnesota, St. Paul, MN
[b] Department of Biological Sciences, Olivet Nazarene University, Bourbonnais, IL
[c] Idaho Department of Lands, Coeur d'Alene, ID
[d] United States Department of Agriculture, United States Forest Service, Forest Health Protection, Boise, ID
[e] Bartlett Tree Research Lab, Charlotte, NC

Over the past two decades, several high-profile tree-killing insects such as mountain pine beetle and emerald ash borer have expanded their ranges. Less damaging insects undergoing range expansions are easy to miss but could become problematic if new hosts are encountered or natural enemies are absent. In this presentation, we detail the recent discovery of the eastern five-spined ips (*Ips grandicollis* Eichhoff) in Idaho and Utah. Detections in Utah and Idaho are the westernmost occurrence in North America known to date. *Ips grandicollis* is native to eastern North America, but we present evidence of westward movement in recent decades. Although widespread damage is not expected, the insect's behavior in western North America is not yet well understood.

Goldspotted oak borer and walnut twig beetle, domestic invasive species from the western U.S.

Andrea R. Hefty[a]
[a] USDA Forest Service, Forest Health Protection, San Bernardino, CA

The walnut twig beetle (*Pityophthorus juglandis* Blackman [Coleoptera: Scolytidae]) and goldspotted oak borer (*Agrilus auroguttatus* Schaeffer [Coleoptera: Buprestidae]) are domestic invasive forest pests in North America that impact urban, commercial, and natural forests. A simplified pest risk map uses insect temperature tolerances and host range to show where

pests are likely to survive and most importantly, likely to not survive. In 2016, Hefty et al. completed a national risk map for *P. juglandis*. It appears that established populations in Ohio continue to be limited by cold temperatures. Along the Front Range of Colorado, despite cold temperatures, urban black walnut is likely extirpated due to *P. juglandis*-caused mortality. Venette et al. published a risk map for *A. aurogutattus* in 2015 for CA. National Forest managers use this map for monitoring and management plans. The public can access the risk map through an online Story Map (Esri) at www.gsob.org. The interactive map shows where goldspotted oak borer is established and spreading, likely to survive, less likely to survive, or unable to survive. Using this information, homeowners can determine if their trees are at risk and which management options are most suitable for their area.

Forest insects from Mexico and Central America: cause for concern?

Jorge E. Macias-Samano[a]
[a] Coquitlam, British Columbia, Canada

Without a doubt, Mexico and Central America have invasive forest insects and diseases. However, very few of them are recognized and their movements are much less monitored. Attention is centered in those that are affecting exotic tree species in plantations raher than in native and natural forest ecosystems. Government agencies on the Mesoamerican region are well organized and follow international standards when it comes to plant health with an agricultural perspective. Mexico is just starting to merge the plant and forest health approaches to exotic invaders. Forest health sections of government from Central America countries are learning about the existence and importance of them. Just recently, they had a regional effort, supported by FAO and OIRSA (regional Plant Protection Agency), to analyze the need to have their plant health and forest health sections working together on this topic, and they are aiming to start strengthening their diagnostic laboratories capacities and legislations.

Simplified risk assessments for domestic invasive species

Robert C. Venette[a,b*] and Amy C. Morey[b]
[a] USDA Forest Service, Northern Research Station, St. Paul, MN
[b] Minnesota Invasive Terrestrial Plants and Pests Center, University of Minnesota, St. Paul, MN

Not all invasive species come from overseas. Forest pests, for example, constrained by geophysical barriers, may be native to portions of a country (i.e., are domestic) but not yet occur in all ecosystems within the country where they could thrive. As a result, interstate movement of goods (e.g., firewood, wood slabs, or timbers) that might harbor these species could present as much ecological risk as foreign imports. Measures to prevent the introduction of domestic invasive species to naïve ecosystems should be more cost-effective than reactive responses. The practical challenge then becomes to identify the most threatening domestic invasive species to different ecosystems and identify the minimum interventions necessary to prevent their introduction. Simplified pest risk assessments emphasizing the potential magnitude of impact provide an efficient means to triage potential species of concern. We discuss the application of such an approach for walnut twig beetle, *Pityophthorus juglandis*, and mountain pine beetle, *Dendroctonus ponderosae*, two US domestic species for which the Minnesota Department of Agriculture maintains exterior quarantines. In both cases, the simplified assessments benefited from empirical studies to assess pest risk to the regions.

Tracking invasive species moving domestically

Andrew D. Graves[a*], Gabriel G. Foote[b], John P. Formby[c], Monica L. Gaylord[d], Irene D. Lona[e], Alyssa McAlexander[f], Joel D. McMillin[d], Lori J. Nelson[g], and Megan A. Siefker[h]
[a] USDA Forest Service, Forest Health Protection, Albuquerque, NM
[b] Department of Entomology, University of California, Davis, CA
[c] New Mexico Forestry Division, Santa Fe, NM
[d] USDA Forest Service, Forest Health Protection, Flagstaff, AZ
[e] Department of Entomology, University of Arizona, Tucson, AZ
[f] Arizona Department of Forestry and Fire Management, Phoenix, AZ
[g] USDA Forest Service, Pacific Southwest Research Station, Davis, CA
[h] Dept. of Plant Pathology, University of California, Davis, CA

Mediterranean pine engraver (MPE), *Orthotomicus erosus*, was originally discovered in North America in the southern central valley of California in 2005. Survey trapping from 2016 to 2018 revealed a relatively continuous population from Barstow (San Bernardino Co.), CA to Mesquite (Clark Co.), NV. In 2018, it was also detected at two locations in the Phoenix metropolitan area (Maricopa Co.), AZ and has since been found throughout Maricopa County. An extended trapping survey, during 2018 and 2019, did not detect MPE in Tucson, AZ; Deming, Las Cruces, or Williamsburg, NM; or El Paso, TX. We have not caught any beetles in New Mexico or Texas to date. In Arizona, MPE has been trapped in Phoenix and Kingman (Maricopa and Mohave Co., respectively). Cochise Co., Graham Co., and Pima Co., AZ were all negative. At this point, our survey has not linked the distribution to traditional forest landscapes on native trees and it is suspected that this beetle's movement is being aided by human transport. With the potential broad host range of this insect (nearly all lab-tested conifers) and its proximity to native forests, there is concern that impacts could be substantial. The projected outcome of this monitoring and detection step is to determine the current distribution of this pest at a finer scale in hopes of retarding future landscape-level spread through targeted management of infested wood. This project also highlights the need for collaboration among land managers to track the interstate movement of invasive species within the U.S.

C – Range expansion and climate change

Moderator: Mike Howe[a]
[a] University of Wisconsin-Madison

Climate change and increasing drought have the potential to alter the distributions, extents, and severities of forest pest species. This session focused on new reports of range expansions by irruptive forest pests, how extreme heat and longer growing seasons have the potential to alter tree physiology, projections of climatic suitability for possible invasive species, and how a native-invasive pest has expanded in range and affected high elevation forests. Further, this session provides some outlook on possible emerging threats as climate continues to change.

Outbreaks and range dynamics of baldcypress leafroller in the southeastern U.S.

Samuel F. Ward[a] and Kristy M. McAndrew[a]
[a] Mississippi State University

Several recent outbreaks of native forest insects have been unprecedented in their extent and/or severity. The first recorded outbreak of baldcypress leafroller (*Archips goyerana* Kruse; Lepidoptera: Tortricidae), a native defoliator of baldcypress, began in Louisiana in 1983. For years following the onset of the outbreak the causal agent was believed to be a congener, fruittree leafroller (*A. argyrospila* Walker), as baldcypress leafroller was not formally described until 2000. The outbreak is still ongoing, surpassing 100,000 hectares of defoliation in 2017 alone, but has remained confined to southern Louisiana. However, baldcypress leafroller has been reported from Mississippi and the range of baldcypress extends across the southeastern US and reaches southern portions of the midwestern and northeastern US. The range limits of endemic populations of baldcypress leafroller and factors inhibiting such populations from reaching epidemic levels remain unknown. A quantitative analysis of the initiation, persistence, and spread of defoliation in Louisiana will be presented along with a summary of (i) previously reported evidence for drivers of the outbreak and (ii) ongoing efforts to quantify the range dynamics of epidemic and endemic populations.

It’s a dry heat: How trees reprioritize carbon in a hotter, drier world and the potential impacts for bark beetle ecology

Amy Trowbridge[a]
[a] University of Wisconsin-Madison

Heat and drought affect plant chemical defenses and thereby plant susceptibility to pests and pathogens. Yet, our understanding of the impacts of heat and drought on defense is primarily based on data from potted seedlings, making it unclear how older age classes respond to stress. Furthermore, the carbon pools that support secondary metabolism under predicted drought stress are largely assumed. We measured needle and woody tissue secondary metabolites and primary physiology from mature *Pinus edulis* during a unique temperature and drought manipulation field experiment. While heat had no effect on total monoterpene concentrations, trees under combined heat and drought exhibited ~85% and 35% increases in needle and woody tissue, respectively, over multiple years. Physiological variables explained less than 10% of the variation in total monoterpenes for both tissue types while starch and glucose + fructose measured one-month prior explained ~25% of woody tissue total monoterpene concentrations. Notably, some key monoterpene compounds with known roles in bark beetle ecology decreased. These shifts may make trees more favorable for bark beetle attack rather than well-defended, which one might conclude if only considering total monoterpene concentrations. Our results point to cumulative effects of heat and drought that reprioritize specific carbon pools toward defense.

The importance of energy-water limitation threshold in drought impact studies

Joan Dudney[a]
[a] University of California-Santa Barbara

Forest diebacks have increased in magnitude in many regions in response to greater water limitation. "Hotter droughts" are predicted to increase under climate change and result in significant restructuring of forest composition and ecosystems services. Many drought-related studies, however, focus on water limited systems, where water—not energy—poses the greatest constraint on photosynthesis. Contrary to expectation, hotter, drier conditions in energy-limited systems may cause greater growth, as the growing season is extended. Thus, identifying the location of the energy-water limitation threshold is critical to predict forest mortality under climate change. Here we assess the impacts of the recent extreme drought in California (~2012-2015) on whitebark pine across the central and southern Sierra Nevada. We use a combination of over 700 tree-rings and over 1,000 stable isotope samples to test whether extreme drought led to greater growth or greater physiological stress. We show that during extreme drought, the energy-water limitation threshold shifted upslope into higher elevation forests. Trees growing near this threshold experienced some physiological stress, but trees far from this threshold experienced positive growth. These results suggest that extreme drought has a more nuanced effect on average productivity for forests that occur across strong climatic gradients.

Suitability of current and future climates in Canada and the United States for the potential establishment of the European spruce bark beetle*, Ips typographus*

Kishan Sambaraju[a] and Chantal Côté[a]
[a] Canadian Forest Service

Abstract

Non-native pest introductions pose a serious threat to forest health worldwide. In North America, exotic bark beetles are commonly intercepted at the ports of entry, and among the species encountered, the European spruce bark beetle (*Ips typographus* L.) is one of the most frequent. Native to Eurasia, this species causes serious damage to Norway spruce (*Picea* *abies* (L.) H. Karst.) in its indigenous range; however, *I. typographus* also has the capacity to survive and reproduce on important North American spruce species. Climate plays an important role in regulating multiple biological and ecological processes in *I. typographus* such as development rate, flight, voltinism, and population dynamics. We used species distribution models (SDMs) to assess whether climates in Canada and the United States are suitable for the potential establishment of *I. typographus*. We also wanted to assess future geographic shifts in climatic suitability in this region under climate change. Species distribution models are modeling algorithms that associate species occurrences with predictors such as climate variables and can be used to characterize habitat suitability for a target species as well as to quantify spatio-temporal shifts as environment changes. Using multiple SDMs, we linked the distribution of *I. typographus* in Eurasia with biologically relevant climatic variables that likely play important roles in limiting the distribution of this insect. We then used a consensus model to project the climatic suitability of Canada and the United States for *I. typographus*. Preliminary results suggest that climatic conditions are currently suitable in the United States and western Canada for *I. typographus*. Climatic suitability will improve in the future and northward shifts in suitable zones will occur under climate change.

Background

Non-native pest invasions are a worldwide concern as some of these events could seriously impact natural forest ecosystems or even cause disappearances of tree species that may play critically important ecological roles in their habitats (Lovett et al. 2016). From an economic perspective, successful establishment and spread of invasive exotic pests in urban areas could entail unacceptable costs such as those for tree removal and replacement, among other expenses (Aukema et al. 2011). Introductions and establishments of forest insects and pathogens are closely associated with the volume of imports of overseas goods and commodities (Aukema et al. 2010, Lovett et al. 2016). Wood materials used for packaging such as crates and pallets and imports of live plants are important pathways of entry of exotic forest pests into North America (Allen and Humble 2002, Haack 2001, Liebhold et al. 2012).

Bark beetles (Coleoptera: Curculionidae: Scolytinae) constitute a large proportion of intercepted non-native insects in woody materials at the ports of entry in Canada and the United States (Humble and Allen 2006, Haack 2001, Haack 2006). The European spruce bark beetle (*Ips typographus* L.) is one of the commonly intercepted bark beetle species. In its native range in Eurasia, *I. typographus* causes serious damage to Norway spruce (*Picea abies* (L.) H. Karst.). *Ips typographus* has the capacity to successfully develop on major spruce species from North America (Okland et al. 2011). However, despite frequent interceptions of *I. typographus*, successful establishments have not been reported to date in North America. Climate plays an important role in the biology and ecology of *I. typographus* by influencing different processes such as development rate, flight timing, voltinism, and population dynamics in its native range (Faccoli et al. 2009, Jönsson et al. 2007, Wermelinger et al. 2004). Given the role of climate and high interception frequency at the ports of entry, it is possible that climate change-accompanied temperature increases, extreme droughts, and/or other anomalous weather events could favor establishment of *I. typographus* in North America should the insect escape detection and exceed some critical population threshold for successful colonization.

In this work, we used species distribution models (SDMs) to assess whether climates in Canada and the United States are suitable for the potential establishment of *I. typographus*. Species distribution models associate occurrences of species with biologically and ecologically relevant variables to characterize habitat suitability over space and/or time (Elith and Leathwick 2009). Climate-based suitability modeling using SDMs could provide information on establishment potentials of non-native pests, complementing other approaches (e.g., phenology models) performing similar analyses (Bentz et al. 2019). This in turn could help in assessments of ecosystem services and commodity values at risk in case of successful establishment.

Objectives

The main objectives of this work were to 1) develop maps of climatic suitability for *I. typographus* for Canada and the United States using the SDM approach, and 2) assess future geographic shifts in climatic suitability in this region under climate change.

Methods

Occurrence data for *I. typographus* were collected from different sources (1973-2013) including the Global Biodiversity Information Facility (GBIF) database and the research literature (n = 2013). After exclusion of incomplete and duplicate records, and spatial filtering at 50 km to account for clustering-induced spatial bias, 250 presence points remained. We also generated 2000 pseudoabsence points across the range of Norway spruce in Eurasia, as true absences were unavailable.

Data for 19 bioclimatic variables for current (1970-2000) and future periods (2021-2040, 2041-2060, 2061-2080, and 2081-2100) were downloaded from WorldClim website (www.worldclim.org) at 10 min (0.167° x 0.167°) resolution. The raster data were then aggregated to 0.5° x 0.5° resolution considering potential spatial errors in the records. Six out of 19 variables were retained after excluding highly correlated variables ($r = \geq|0.7|$). The variables used in models included mean diurnal temperature range (BIO2), isothermality (BIO3), mean temperature of warmest quarter (BIO10), mean temperature of coldest quarter (BIO11), annual precipitation (BIO12), and precipitation of warmest quarter (BIO18). For future projections of climatic suitability, we used averages of the chosen bioclimatic variables derived from three general circulation models (CanESM5, CNRM-ESM2-1, MIROC-ES2L) under two Shared Socio-economic Pathway (SSP) scenarios (SSP2-4.5 and SSP5-8.5; Meinshausen et al. 2020).

Seven modelling algorithms were used in developing models of climatic suitability for *I. typographus* in R v. 4.0.4 via the Biomod2 package (Thuiller et al. 2020): generalized linear model (GLM), generalized additive model (GAM), classification tree analysis (CTA), artificial neural networks (ANN), generalized boosting model (GBM), random forest (RF), and surface range envelope (SRE). We developed a consensus model based on individual models of good predictive ability (True Skill Statistic: TSS ≥ 0.7) and projected model results for Canada and the United States for current and future climates.

Main findings

Preliminary results indicate that all individual models except SRE performed well (TSS > 0.8). Maps based on the consensus model suggest that British Columbia, southwest Alberta and

Newfoundland in Canada are suitable for *I. typographus* and will remain so in the future. As climates warm over the coming decades, forests in eastern Canada (southern Ontario, southern Québec, and Labrador) and northwestern Canada will become more favorable. Spruce forests in the contiguous United States will consistently remain suitable for *I. typographus*. Climatically suitable locations will increase in Alaska toward the end of the 21st century.

Keywords: bark beetles, *Ips typographus*, climatic suitability, mapping, species distribution models

Acknowledgments: We thank Natural Resource Canada's Pest Risk Management program for funding this work. We are grateful to Global Biodiversity Information Facility and WorldClim, including individuals and agencies involved in making climate data available, for their efforts in maintaining the databases.

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Emigration or establishment? Exploring mountain pine beetle range expansion into whitebark pine in British Columbia

Michael Howe[a], Allan Carroll[b], Claudio Gratton[a], and Kenneth F. Raffa[a]
[a] University of Wisconsisn – Madison
[b] University of British Columbia, Department of Forest and Conservation Sciences

Warming temperatures are allowing native insect herbivores to expand into regions that previously exceeded their thermal tolerance, encounter new host species, and pose significant threats to native communities. However, the dynamics of these expansions remain poorly understood, particularly in the extent to which outbreaks remain reliant on emigration from historical hosts or are driven by local reproduction within novel hosts in the expanded range. We tested these non-mutually exclusive hypotheses using spatially explicit data on mountain pine beetle (*Dendroctonus ponderosae*), which historically undergoes intermittent outbreaks in low-elevation lodgepole pine (*Pinus contorta*), but is now causing severe mortality in a high-elevation endangered species, whitebark pine (*Pinus albicaulis)*. We compiled data from 2000-2019 across British Columbia, Canada, at 1 km^2 resolution, and analyzed spatiotemporal patterns of beetle infestations, lodgepole pine distributions, expansion into habitats dominated by whitebark pine, and the likelihood of future outbreaks in all pine communities under simulated conditions. Overall, we found strong support for the hypothesis of emigration from the historical host species continuing to be a major driver of outbreaks in the more recently accessed host. First, beetle population pressure was consistently the best predictor of infestation severity in both lodgepole and whitebark pine, and appeared to be mostly unidirectional from lodgepole to whitebark pine. Second, infestations in lodgepole pine were of a longer duration than those in whitebark pine, which appeared too brief to sustain transitions from endemic to eruptive dynamics. Further, resource depletion appears to drive emigration

from lodgepole pine, whereas in whitebark pine drought appears to favor establishment of immigrants although bioclimatic factors and stand structure preclude self-sustaining outbreaks. Finally, we project that most pine in British Columbia will be at risk in the event of a new major outbreak. We describe implications for conserving and protecting whitebark pine and to other climate-driven range expansions.

D – Open Session 2

Moderator: Ashley Schulz[a]
[a] Colorado State University

Functional traits drive bee community responses to habitat variability in managed southeastern U.S. forests

Christine Cairns Fortuin[a] and Kamal J.K. Gandhi[a]
[a] D.B. Warnell School of Forestry and Natural Resources, University of Georgia, Athens

Overview of problem area

Wild bees represent many taxa with differing life strategies, life cycles, and dietary needs. Nearly all wild bees require a variety of resources to complete their life cycles including pollen and nectar, nesting substrates such as detritus, deadwood, and/or cavities in standing trees, and nesting materials such as mud, resin, and leaves (Roulston and Goodell 2011). Anthropogenically-altered habitats often create forage opportunities for bees, however wild bees also require nesting habitat which may be more likely found in undisturbed areas (Neame et al. 2013), and availability of nesting resources can be a limiting factor for wild bee diversity (Hudewenz and Klein 2013; Potts et al. 2005). Various forest management practices such as thinning and group selection create heterogeneity in the landscape, and these practices have often been correlated to bee diversity (Taki et al. 2010, Hanula et al. 2015, Rodríguez and Kouki 2017, Mullally et al. 2019). Heterogeneity in landscapes thus appears to infer value in terms of bee diversity, however forest-specialist species are understudied, and displacement of forest-specialist species in heterogenous habitats may not be revealed with traditional metrics of diversity and abundance (Winfree et al. 2011). The type and degree of response to habitat heterogeneity created by anthropogenic activity will be mitigated by traits of individual bee species within the community (Banaszak-Cibicka and Żmihorski 2012). Thus, a functional trait approach to examining bee community response to habitat heterogeneity in forests may reveal different patterns than species diversity alone.

Objectives of study

Three objectives of the study were: 1) to determine bee population and community level responses to site type including abundance, diversity, and community structure; 2) to assess how bee communities respond to site-types as based on functional traits; and 3) to determine how nest guilds respond to habitat variability, and whether nest site availability can predict nest guild composition.

Methods

We sampled wild bees in 2017 and 2018 in Whitehall Forest, University of Georgia in Clarke County, Georgia and Hardman Memorial Park in Jackson County, Georgia. Three site-level treatments were chosen: 1) mature upland hardwood (>25 yr, n=4); 2) managed pine (>15 yr, n=4); and 3) recent pine clearcut (within 1-2 years, n=4). Sites within the same county were a minimum of 500 m distant from each other. Each site was sampled for the following nesting habitat indicators: snags (standing dead trees), duff layer depth (the depth of the top layer of organic soil), the volume of downed woody debris (lying dead wood), and the decay class of downed wood. All measurements were conducted utilizing USDA Forest Inventory Analysis (FIA) methods (United States Department of Agriculture 2016). Bee species were identified to species and assigned to functional categories based on size, sociality, nesting, peak flight season, and diet, following criteria similar to other bee community studies (Bartomeus et al. 2013, Harrison et al. 2018)

Main findings

Both functional evenness and functional dispersion were highest in the hardwood forests, followed by pine forest, with a significant decrease in the cleared areas. Conversely, species richness and abundance followed the opposite pattern, and were highest in clearcut areas. Thus, while clearcuts supported a high level of species diversity, they had a low level of trait diversity. Conversely, while hardwood and pine forests supported higher levels of trait diversity, species diversity was lower. Distributions of trait classes revealed that fewer functional groups were represented in clearcuts compared to the forest communities, with clearcuts dominated by soil nesting and social bees, while hardwood forests supported more cavity and softwood nesting groups, as well as solitary and early season bees. This finding suggests more unique niche opportunities in hardwood forests, leading to higher functional evenness and higher beta diversity compared to clearcuts. Habitat openness explained 43% of the variation in species composition. Nesting habitat indicators explained 53% of the variation in nesting guilds across habitats, and nesting guilds had differential responses to nesting habitat variables, with cavity nesting bees responding strongly to downed wood volume, and soil nesting bees more driven by habitat openness and shallow organic soil layer. Hence, we can expect responses of wild bee communities to be strongly influenced by nesting habitat structure and composition within managed forests, and not solely floral resources. Hardwood forests may be a source of functionally diverse groups of bees, and maintaining patches or swaths of hardwood forests with some downed wood accumulation may be critical for maintaining functional diversity of bees in managed forested ecosystems.

Keywords: clearcut, functional traits, hardwood forests, managed pine, nesting habitat, wild bees

Acknowledgements: We thank the following for their input and assistance: Berry Brosi (Washington State University), Brittany Barnes, Lea Clark, Keith Delaplane, and Elizabeth McCarty, (University of Georgia), Michael Del Rossi (Columbia Law School), Jamie Botsch (University of Wisconsin), and Sam Droege (USGS Patuxent Wildlife Research Center). Funding was provided by EPA STAR fellowship* to C.C, Fortuin, and by the D.B. Warnell School of Forestry and Natural Resources, University of Georgia.

*This research was developed under STAR Fellowship Assistance Agreement no. FP-91781001-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed

by EPA. The views expressed in this abstract are solely those of the authors, and EPA does not endorse any products or commercial services mentioned in this abstract.

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Emerging molecular technologies for bark beetle management

Bethany R. Kyre[a] and Lynne K. Rieske[a]
[a] Department of Entomology, University of Kentucky, Lexington, KY

Changing climate patterns spurred on by anthropogenic activities have overwhelmed traditional management strategies and allowed *Dendroctonus* bark beetles to expand their ranges. This alarming geographic range expansion, coupled with persistent outbreaks in their historic ranges, are evidence for the need for novel and innovative tools for managing bark beetles. Fortunately, there are emerging molecular technologies that are applicable for next generation management, specifically gene silencing through RNA interference or RNAi. RNAi is a naturally occurring antiviral response that can be artificially induced through the introduction of lab synthesized double stranded RNA (dsRNA). The dsRNAs guide the RNA induced silencing complex (RISC) to cleave and degrade complimentary messenger RNA (mRNA) prior to translation and construction of critical proteins, thus silencing gene function. Initial proof of concept studies in southern pine beetle (SPB), *Dendroctonus frontalis*, and mountain pine beetle (MPB), *D. ponderosae,* demonstrated the efficacy of dsRNAs to silence three genes necessary for basic life functions: heat shock protein (*hsp*), shibire (*shi*), and inhibitor of apoptosis (*iap*), leading to significant mortality.

RNAi technology is touted as a highly specific approach to pest management as an exact match of at least 16 nucleotides between introduced dsRNAs and target genes is required for appropriate mRNA binding. Interspecies non-target silencing is rare and most likely to occur in congeners. Thus, the efficacy of dsRNAs to affect gene silencing between congenerics was investigated. dsRNAs targeting SPB were ingested by MPB, and reciprocal dsRNAs targeting MPB were ingested by SPB. Gene expression analyses revealed significant silencing in both species. Analysis of sequence alignments of target genes corroborated gene silencing results, and further *in silico* analysis of multiple *Dendroctonus* species revealed potential for species specific dsRNAs to induce gene silencing across the genus. Congeneric non-target effects could play an important beneficial role in genus-specific mitigation strategies where species overlap may occur, however, intraspecies genetic variation should be considered during target gene selection and primer design.

Primers showing success in SPB populations collected from the southeastern United States were tested on other geographically distinct populations collected from SPB's northern most expanded range in New York, and the southern portion of its endemic range in Mexico. The dsRNAs evaluated demonstrated differential gene silencing in adult SPB both between and within distinct populations. Subtle differences in gene expression due to population type, geographic location, host plant, etc., could lead to changes in gene expression, possibly impacting gene function or immune responses to dsRNAs. The need for further genomic sequencing of bark beetles is clear.

Lastly, while a broader understanding of the genetic under-pinnings of bark beetle invasiveness is warranted, so too is the investigation of deployment methods capable of landscape level impacts. One solution may lie in the transformation of fungal symbionts to express bark beetle specific dsRNAs, thus creating a self-perpetuating vector that can be driven into a population and carried from one generation to the next.

Given the significance of SPB and MPB as recurring forest pests, the unprecedented expansion of their geographic ranges, colonization of novel hosts, and the difficulties associated with forest level management, it's clear that gene silencing could provide a powerful tool for tomorrow's bark beetle management.

Temperature effects on spotted lanternfly phenology

Melody A. Keena[a], Devin Kreitman[b], Anne Nielsen[c], and George Hamilton[b]

[a] USDA Forest Service, Northern Research Station, Hamden, CT

[b] Rutgers, The State University of New Jersey, Brunswick, NJ

[c] Rutgers Agricultural Research & Extension Center, Rutgers, The State University of New Jersey, Bridgeton, NJ

Abstract

Lycorma delicatula (White) (spotted lanternfly [SLF]), an invasive planthopper from Asia, is an emerging pest in North America. Good phenology models based on the responses of SLF to a broad range of temperatures are needed for predicting when monitoring for SLF needs to be done, when the right stage is present for application of control methods, and what regions of the US are likely to support SLF populations. This information is also needed to develop protocols for rearing large numbers of SLF for use in bioassays or biological control rearing. Without an efficient laboratory rearing methodology for SLF, mass rearing of any discovered natural enemies needed for field testing or release will be limited, especially outside the infested zone. Efforts to screen pesticides are equally restricted by the resources needed to obtain the large numbers of even aged individuals from natural populations. Year-round mass rearing would allow rapid screening of many pesticides and other monitoring or control methods.

SLF has one generation per year in Korea with nymphs emerging in May and adults appearing in July. Similar occurrence of life stages is observed in Pennsylvania; nymphs begin to emerge in late April, and adults appear around mid-July and lay eggs from early September until first frost (Dara et al. 2015). Little is known about SLF responses to temperature and the only modeling on potential range was done for Korea using CLIMEX and the current range information for populations in Korea (Jung et al. 2017). Egg survival of SLF is associated with winter temperature (Lee et al. 2014) and in laboratory rearing experiments, egg hatch occurs at 56, 27, and 22 days at 15, 20, and 25ºC, respectively. Degree-day (DD) requirements for egg hatch were estimated to be 355 $DD_{8.14}$ (Choi et al. 2012), but no information on biofix is included. Thus, it is currently unknown at what temperatures egg hatch can occur or if SLF uses specific environmental cues to time hatch, such as photoperiod or chilling days. For example, SLF egg hatch was observed in Winchester, VA by D. Pfeiffer on May 9, 2018 which is 266 $DD_{8.14}$ using the parameters from available studies. This suggests that evaluation of egg hatch and nymphal development of the US population is needed to develop precise phenological models and

predict seasonality. The timing of egg hatch is the biofix needed to start the phenology model and the conditions needed could potentially restrict the range of this insect.

Ninety-six egg masses of SLF from five locations in Pennsylvania were obtained in the beginning of April and hatched by the end of May 2019 for use in the nymphal phenology studies. Six groups of 20 SLF each were setup on tree of heaven, *Ailanthus altissima* (Miller), seedlings in tubes at each temperature and were observed daily for mortality and molts. SLF was reared from first instar to adult on *A. altissima* at each of the following constant temperatures: 5, 10, 15, 20, 25, 30, 35, and 40°C. The time spent in each instar and mortality were recorded. For the egg hatch studies, newly laid SLF eggs (<14 d old) from three Pennsylvania sites were collected in October 2019. The egg masses were held at three constant temperatures (10, 15, or 20°C) or exposed to low (5 and 10^{o}C) temperatures for 0, 7, 28, 56, or 84 d followed by incubation at 25°C while maintaining the photoperiod of 16:8 (L:D).

The lower threshold for egg development was estimated as 7.39°C. Eggs held at constant 10, 15, and 20˚C were estimated to require 635, 715, and 849 $DD_{7.39}$, respectively, to develop. Egg hatch rates were highest when held at a constant 15˚C, though high rates were also obtained when eggs were held for 84 days at 10°C, then moved to 25°C. Almost all eggs enter diapause since very few eggs were able to hatch when moved to 25°C after 7 days of chill at either 5 or 10°C. Nymphal developmental rate increased with temperature from 15°C to 30°C for all instars, then declined again at higher temperatures. Nymphal survival was lower at 35°C than between 15-30°C for all instars, and first instars placed at 5, 10, and 40°C all died without molting. The lower developmental threshold was found to be 13.00±0.42°C for first instars, 12.43±2.09°C for second instars, 8.48 ± 2.99°C for third instars, and 6.29 ± 2.12°C for fourth instars. The DD requirement for nymphs in the previous instar to complete development to reach the second instar, third instar, fourth instar, and adult was 166.61, 208.75, 410.49, and 620.07 DD (base varied), respectively. These results provide key data to support laboratory-rearing efforts, the development of phenology models and help identify the potential range of SLF in North America. Other studies to evaluate the effects of heat waves and cold snaps on development are ongoing that will further define the phenology of this insect. The studies reported here have both been published (Keena and Nielsen 2021, Kreitman et al. 2021).

Keywords: phenology, hatch, development, survival, temperature

Acknowledgements: We thank P. Moore, J. Richards, and N. Lowe for technical assistance. We also thank D. Mikus, T. Trotter, B. McMahon, X. Wu, I. Urquhart, M. Barr, L. Schmel, B. Walsh, and D. Long for assistance in collecting egg masses. This work was funded in part by USDA APHIS PPQ S&T interagency agreements 19-8130-0840-IA and 20-8130-0840-IA with the Forest Service and AP19PPQS&T00C117 cooperative agreement with Rutgers University. This work was also supported in part by the US Forest Service Northern Research Station.

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Impact of biological control agents on Canadian emerald ash borer parasitoids

Chris J.K. MacQuarrie[a], Mary Gray[a], Gene Jones[a], and Tim Ladd[a]
[a] Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, ON, Canada

Three biological control agents have been released in Canada for the control of emerald ash borer. These species were released as part of the US-led effort to reduce the impact of the pest on ash trees in North America. The first releases of *Tetrastichus planipennisi* were made in 2013 with *Oobius agrili* and *Spathius galinae* following in 2015 and 2017. Beginning in 2018, we initiated experiments to examine the impact and dispersal of these parasitoids in the Canadian ash ecosystem. These experiments were intended to determine if the parasitoids were contributing to population regulation, and to determine if and how far the insect has spread. To examine the impact of the parasitoids on population dynamics we used a series of sequential caging studies to partition the attack of parasitoids on resident emerald ash borer in some of the oldest release sites. In our dispersal experiment, we used pan traps established at 2-30 Km from the oldest release sites to examine dispersal in southwestern Ontario, Canada. The results of these experiments will be used to estimate the contribution of these biological control agents to regulation of emerald ash borer in Canada.

The effect of host plant on the nymphal development of spotted lanternfly

Devin Kreitman[a], Melody A. Keena[b], Anne Nielsen[c], and George Hamilton[a]
[a] Rutgers, The State University of New Jersey, Brunswick, NJ
[b] USDA Forest Service, Northern Research Station, Hamden, CT
[c] Rutgers Agricultural Research & Extension Center, Rutgers, The State University of New Jersey, Bridgeton, NJ

Lycorma delicatula (White), an invasive planthopper from Asia, is an emerging pest in North America that was first detected in 2014 (Dara et al. 2015). Even though it has a broad host range, it is heavily associated with *Ailanthus altissima* (Miller). Due to its polyphagous nature, it is important to understand how host plants affect its phenology. Previous work on this insect's phenology at different temperatures only used *A. altissima* as a host so this current work will expand upon that (Kreitman et al. 2021).

Nymphs were reared on the following host plants at a constant temperature (25°C): *Acer rubrum* (L.), *A. altissima*, *Celastrus orbiculata* (Thunberg), *Ocimum basilicum* (L.), *Rosa multiflora* (Thunberg), *Salix babylonica* (L.), and *Vitis labrusca* (L.). The development rate and weight were compared for nymphs of each instar reared on each host.

First and second instar nymphs developed at similar rates on all hosts that were tested. It was found that third instar *L. delicatula* nymphs took longer to develop on *S. babylonica* than on *A. altissima* or *V. labrusca.* Females weighed more and took longer to develop than males in the third and fourth instar. Survival was variable and the number of hosts that it could utilize to complete an instar decreased as instar increased. Implications of these findings will be incorporated into the phenology modeling that is underway.

Keywords: phenology, development, survival, hosts

Acknowledgements: We thank P. Moore and N. Lowe for technical assistance. We also thank D. Mikus, T. Trotter, B. McMahon, X. Wu, I. Urquhart, M. Barr, and L. Schmel for assistance in collecting egg masses. This work was funded in part by USDA APHIS PPQ S&T interagency agreement with the Forest Service and cooperative agreement with Rutgers University. This work was also supported in part by the US Forest Service Northern Research Station.

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Subterranean survivorship, timing of emergence, and potential supplementary diet of *Laricobius* spp. (Coleoptera: Derodontidae), biological control agents for the hemlock woolly adelgid

Jeremiah R. Foley IV[a], Albert E. Mayfield III[b], and Scott M. Salom[a]
[a] Department of Entomology, Virginia Tech, Blacksburg, VA
[b] USDA Forest Service, Southern Research Station, Asheville, NC

Laricobius spp. share the Derodontidae clade with three other family members (*Derondontus*, *Nothoderodontus*, and *Peltastica*) and together, are collectively known as the "tooth-necked" fungus beetles. From the literature, all genera except *Laricobius* consumes fungi. *Laricobius* spp. are specialist predators of Adelgidae and presumably no longer feed on fungi. Additionally, *Laricobius nigrinus* and *L. osakensis* have been used as biological control agents for the hemlock woolly adelgid (HWA), *Adelges tsugae*, for the past 16 and 10 years, respectively. *Laricobius* spp. spend half of their univoltine life cycle within the arboreal habitat of hemlocks and the other half beneath hemlocks, in a subterranean habitat. Most of the literature on *Laricobius* spp. has focused on their arboreal habitat and few studies have documented their subterranean biology. Historically, lab-rearing these beetles has been limited by significant mortality (~40%) during the subterranean portion of this insects' life cycle (Foley et al. 2021). Herein, we describe the subterranean biology of *L. nigrinus* and *L. osakensis* in terms of their supplementary diet and field survivorship.

Keywords: biocontrol, predator, conservation biology, HWA

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Great Lakes Basin Forest Health Collaborative: What it's all about

Rachel Kappler[a], Courtney Blashka[a], David Burke[a], Eboni Hall[b], Carolyn Pike[c], and Jennifer Koch[d]
[a] The Holden Arboretum, Kirtland, OH, USA
[b] American Forests, Washington, DC, USA
[c] USDA Forest Service, State and Private Forestry, Eastern Region, West Lafayette, IN, USA
[d] USDA Forest Service, Northern Research Station, Delaware, OH, USA

Eastern forests, including those in the Great Lakes Basin, have been severely impacted by invasive insects and diseases culminating in decreased biodiversity, altered forest ecology, and reduced ecosystem services. Five native ash species (*Fraxinus* spp.) are threatened with extinction as a result of the emerald ash borer (*Agrilus planipennis*) including green ash (*F. pennsylvanica*), an important riparian species and black ash (*F. nigra*), the loss of which has the potential to convert northern wetland forests to open marsh. Common northeastern forest types containing beech (*Fagus grandifolia*) and eastern hemlock (*Tsuga canadensis*) are under

siege from beech bark disease, beech leaf disease, hemlock woolly adelgid (HWA), and elongate hemlock scale. The newly formed Great Lakes Basin Forest Health Collaborative (GLB FHC), a partnership with Holden Forests & Gardens, American Forests and the USDA Forest Service, was formed to help advance resistance breeding for these important tree species. The primary mission is to use a participatory approach by establishing a network of partners and provide training and technology transfer. In turn, partners provide volunteers and other resources to work together with the FHC on activities including the identification of survivor trees with potential resistance, clone bank and/or seed orchard establishment, and seed collections, with the long-term goal of producing improved seed sources to restore impacted forests. We are currently developing a partner network within the GLB for initial projects that include the identification and propagation of lingering ash trees that have survived long-term EAB infestation and seed collections for conservation of eastern hemlock. We anticipate expanding to projects in the future that involve breeding for HWA resistance and identifying beech trees that remain healthy in areas heavily impacted by beech leaf disease. Once networks are established, the FHC can quickly mobilize to address new damaging pests as they arise.

CONCURRENT SESSION 3

A – When old plays work and when do we need to rewrite them? Part 1

Moderators: Sandy Smith[a] and Chris J.K. MacQuarrie[b]
[a] University of Toronto John H. Daniels Faculty of Architecture, Landscape and Design, Graduate Department of Forestry
[b] Natural Resources Canada Canadian Forest Service, Great Lakes Forestry Centre

This symposium presents – When do old plays work and when do we need to rewrite them? Managing insect populations can be thought of as developing a playbook of tactics and strategies that seek to exploit weaknesses in the pest's defenses. When we encounter new pests or new outbreaks of old pests, we often draw on the successful plays from the past. However, under climate change, range expansions and invasions of new pests sometimes those old plays may not always work. Using examples from previous successful management of native and invasive pests we will examine how these successful plays have influenced the management of more recent pest problems, and where the old playbook has needed to be re-written.

You shall not pass! Using knowledge on population dynamics to manage spruce budworm

Jacques Régnière[a]
[a] Natural Resources Canada Canadian Forest Service, Laurentian Forestry Centre

Over the last several decades, much has been learned on the ecology, population dynamics, and management of the spruce budworm in eastern Canadian boreal forests. Evidence increasingly supports the idea that this insect is indeed regulated by a multiple-equilibrium system, where populations are kept in check by natural enemies until they escape and rise to outbreak level where negative feedbacks limit their further growth and eventually cause their decline. All of this occurring in a context of high mobility, connecting regional meta-populations through moth migration. We will discuss the evidence for these statements, the ongoing research and modeling, and their implications for pest management.

Keywords: eastern spruce budworm, population dynamics, migration, pest management

The role of native natural enemies in the successful biological control of winter moth in the northeastern United States

Hannah J. Broadley[a,b,c], Joseph S. Elkinton[a,b], and George H. Boettner[b]
[a] Graduate Program in Organismic and Evolutionary Biology, University of Massachusetts
[b] Department of Environmental Conservation, University of Massachusetts
[c] Otis Laboratory, USDA APHIS Plant Protection and Quarantine, Science & Technology

Winter moth, *Operophtera brumata*, a polyphagous caterpillar was accidentally introduced to the northeastern United States in the 1990s. Previous invasions of winter moth in Canada were successfully suppressed following the introduction of two biological control agents from winter moth's native range - *Cyzenis albicans* and *Agrypon flaveolatum*. In our work, we did not use *A. flaveolatum* due to concerns about its host specificity. We established *C. albicans* at sites across the northeastern U.S. and establishment has coincided with a dramatic decrease in winter moth density. However, this success depends on additional mortality from native natural enemies including predators and parasitoids. In the native range of Europe, pupal predators were found to regulate winter moth densities. Further, in the two invasive populations of winter moth in Canada, predation was found to increase following the introduction of the biocontrol agents. We built on this earlier research and, over five field seasons, deployed winter moth sentinel pupae in the field to determine rates of predation and parasitism across a range of winter moth pupae and *C. albicans* puparia densities. Prior to the establishment of *C. albicans* in years when winter moth densities were high, we did not observe density dependent mortality. Since 2016 however, *C. albicans* has become widely established and winter moth densities have decreased to a level comparable to what was found in its native range. We have found that mortality on the pupae was density dependent and thus may stabilize winter moth at low density. Overall, our research shows that mortality on winter moth pupae was already high in the northeast but that the introduced biocontrol agent provides enough additional mortality to render winter moth a non-pest.

Keywords: winter moth, biological control, density dependence, pest management

A new strategy for an old pest: the early intervention strategy against the spruce budworm

Véronique Martel[a] and Rob Johns[b]
[a] Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre
[b] Natural Resources Canada, Canadian Forest Service, Atlantic Forestry Centre

Background

The spruce budworm (SBW), *Choristoneura fumiferana* (Lepidoptera: Tortricidae), is an old pest, but with cyclic outbreaks occurring every 30-40 years (Pureswaran et al. 2016). Each outbreak is slightly different, depending on the forest composition, the climate or our use of the forest. In addition, management strategies have also changed based on (i) growing concerns for the impacts of broad-spectrum insecticides; (ii) our understanding of spruce budworm population dynamics; and (iii) the tools and technological advances that are now available.

Insecticides used

In the 1950s, spruce budworm was managed using the broad-spectrum insecticide DDT, which by the 1970's was largely replaced by a related insecticide, Fenitrothion. Even at the time these insecticides were controversial and elicited significant public concern as captured in the books Silent Spring (Carson 1962) and Budworm Battles (May 1982). These products were eventually replaced by the more narrow-spectrum alternatives of Btk (*Bacillus thuringiensis* var. *kurstaki*) and tebufenozide (note that in the province of Quebec only Btk is used). Both products specifically target larval Lepidopterans and must be ingested. Both also have relatively short half-lives in the environment and are not known to impact non-target animals, with the possible exception of other caterpillars with similar phenology.

Communication

The history of broad-spectrum insecticides used against the spruce budworm and the two published books led to a credibility issue regarding management. This led us to an important conclusion: communication is the key. To address communications needs the Healthy Forest Partnership was formed and brought together different partners from Federal and Provincial governments, Universities and Industries. The communications strategy that arose from this consortium rested on two main principals: (1) CFS and university scientists are leading the research, communication, and outreach regarding all science-related issues; and (2) All public questions and issues will be responded to directly and honestly by experts based on current scientific evidence. Proactive communication and outreach initiatives were thus developed, including: a bilingual website, traditional media proactive campaign, social media posts, blogs, podcasts, kiosks in forests fairs, meetings with forests users in the research field area (i.e. New Brunswick, Canada), etc. A community science initiative was also initiated, thus bringing together two important objectives: obtaining scientific data while increasing outreach (Carleton 2020). All these communication initiatives were conducted in both official languages, which was recognized through two awards received: the Excellence and Leadership in Official Languages Award – awarded to 50 recipients in Canada for the 50th anniversary of the Official Languages Act in 2019 and the Atlantic Federal Council Official Languages Recognition Award in 2020.

Strategy

The change in insecticides used and in transparency from scientists are not the only important changes that occurred during the past two decades. As detailed in Jacques Régnière's talk – *You shall not pass! Using knowledge on population dynamics to manage spruce budworm* – our understanding of the population dynamics has progressed substantially. The most important consequence is that we now know that with the Double Equilibrium Theory (Pureswaran et al. 2016), outbreaks are avoidable – insecticide treatments can affect populations. From the Foliage Protection Strategy, in which the most susceptible areas are treated during outbreaks in order to keep the trees alive until the collapse of populations, we can now aim at preventing the populations from rising to outbreaking levels. This new management approach is called the Early Intervention Strategy (EIS), and is the subject of a research project in New Brunswick, Canada, since 2014 (Johns et al. 2019). The concept is simple: treating areas where spruce budworm populations approach a certain threshold in order to prevent them from reaching outbreaking levels. However, for the EIS to work, the whole area (and only that area) where populations meet the criteria must be treated. If not, the untreated area might become a source of moths. This obviously requires intensive sampling to identify the areas to be treated. EIS has been effective until now, with the population growth being negative for treated sites every year, while the population growth rate was positive for untreated sites every year, except in 2018 when a general decline in spruce budworm was observed throughout the province of New Brunswick. The Early Intervention Strategy is thus an additional tool that can be used at the beginning of the outbreak cycle, though Foliage Protection Strategy remains an alternative strategy when populations are too high for EIS.

Technology

Technology is also a key aspect that can make a huge difference in the management strategy against pests. In the case of the spruce budworm, the most obvious example concerns the use of the egg parasitoid *Trichogramma minutum* for biological control. An important and successful program was established in the 1980s in Ontario (Smith 1990), in which the conditions for successful biological control were established – release rate, timing, etc. The authors also established that ground or aerial releases gave similar results. In their study, the aerial releases were done from a helicopter. About 30 years later, we conducted some additional biological control assays against the spruce budworm following these recommendations. The exact same protocol was followed, except concerning the helicopter. Instead, UAS were used to release the egg parasitoid, making it cheaper, faster, but besides that, being exactly the same (Martel et al. 2021).

Keywords: spruce budworm, management, communication, history

Acknowledgements: We would like to thank the numerous field and lab staff involved in the Early Intervention Strategy. The EIS research is overseen by the Healthy Forest Partnership, a consortium of researchers, landowners, forestry companies, governments, and forest protection experts. Many scientists and staff of industry and government agencies have made important contributions without which the project could not have proceeded.

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Hemlock Woolly Adelgid in eastern Canada

Lucas Roscoe[a]
[a] Natural Resources Canada Canadian Forest Service, Atlantic Forestry Centre

The hemlock woolly adelgid (HWA, *Adelges tsugae* Annand, Hemiptera: Adelgidae) is a serious invasive alien pest of hemlock (*Tsuga sp.*) in eastern North America. Recently discovered in both Ontario and Nova Scotia, HWA threatens to cause extensive mortality in hemlock-dominated forests in both provinces. Consequently, the development and implementation of effective management strategies in threatened areas are of primary importance. Several management strategies exist, including silvicultural management, chemical control and biological control. While an extensive body of knowledge for these methods, developed over several decades of research in the United States, exists, the effectiveness of these methods in eastern Canada is yet to be proven. Studies on the feasibility of these methods are currently underway. It is anticipated that these preliminary evaluations will provide the critical information for the appropriate development and utilization of landscape-level management techniques for HWA in eastern Canada and beyond.

Keywords: hemlock woolly adelgid, pest management

(Wood) boring phenology for the interest of emerald ash borer invasion management

Ken Dearborn[a,b]
[a] University of Toronto John H. Daniels Faculty of Architecture, Landscape and Design, Graduate Department of Forestry
[b] Natural Resources Canada Canadian Forest Service, Great Lakes Forestry Centre

The invasive emerald ash borer has forever altered the eastern forests of North America. Phloem-feeding larvae have strangled ash, *Fraxinus*, in 35 US states and 5 Canadian provinces. Tracking life-stage specific development in growth chambers across biologically-relevant temperatures will increase the accuracy of phenology-based predictions. These growth rates will inform models to mitigate range expansion and predict long-term impacts. For eggs and larvae, 7 and 10 °C appear to be below developmental thresholds with zero eggs hatching and no larvae progressing to second instars. Egg development duration was shorter as temperatures increased from 15 to 35 °C (62 versus 8 days). Larval development within *F.*

pennsylvanica was faster at 30 °C than at 25 °C with more than 50% of larvae completing development from eclosion to prepupae at 30 °C in 45 days. At 30 °C, larvae took residence in mini-bolts at a higher rate in *F. pennsylvanica* (3.31 ± 0.19 larvae/mini-bolt) compared to *F. excelsior* (1.13 ± 0.13). Larval development to the first prepupa took 50% longer in *F. excelsior* than *F. pennsylvanica*. Future work will include more temperatures for both ash species and compare host differences on growth rates. These growth rates will be used to determine where a life cycle can be completed and to enhance biological control release timing.

Keywords: emerald ash borer, phenology, pest management

B – In search of fresh, tractable solutions to the wicked problem of destructive, non-native forest pests

Moderator: Enrico Bonello[a]
[a] Department of Plant Pathology, The Ohio State University

Wicked problems are those that lack a singular solution and change in response to attempts to solve them. Invasions of forest environments by insect pests and pathogens are definitely a wicked problem. The organizational infrastructure for combatting such invasions is decentralized, with responsibilities spread across multiple public and private entities, and as a result, incapable of protecting forest resources. Recent advances, e.g. in host resistance breeding, show promise as tools to rapidly and effectively deal with invasive forest pathogens, but as seen with infectious diseases such as the current COVID-19 pandemic, even the most promising solutions face serious implementation challenges. The COVID-19 pandemic highlights the perils of lack of national and global coordination in combating sinister, destructive pests, and may add needed perspective to the discussion of international approaches to combat invasive forest pests. This symposium will be a forum to discuss fresh solutions to this pernicious issue.

What is wickedness and how does it apply to the forest health crisis?

Geoffrey M. Williams[a] and Damian C. Adams[b]
[a] Department of Forestry and Natural Resources, Purdue University
[b] School of Forest, Fisheries, and Geomatics Sciences, University of Florida

The Anthropocene is characterized by a deteriorating state of our environment and extreme threats to natural systems. Destructive exotic pests have been accumulating and damaging evolutionarily naïve trees at an exponential rate due to the increasing volume of global trade (Ploetz et al. 2013, Showalter et al. 2018). These novel encounters have led to iconic, devastating, landscape-transforming epidemics. Without action, the onslaught caused by destructive invasive organisms will continue to greatly accelerate a massive transformation of forest ecosystems worldwide. Invasional meltdown, a loss in associational resistance due to decreased host diversity, threatens to exacerbate the problem by further increasing the susceptibility of remaining species to destruction. Thus, forests are at a tipping point due to these and a long list of other connected threats. But we argue that foremost among these is society's reactive and often passive stance toward protecting and managing this vital and irreplaceable natural resource.

As scientists, we can learn how to approach the fundamentally social dilemma posed by the forest health crisis by studying lessons learned from similar problems through the frameworks of wickedness, common pool resources, and the policy cycle. The forest health crisis has several attributes that make it a wicked problem. First, there is fundamental disagreement about the definition of the problem among key stakeholders whose cooperation is needed to solve it. Efforts to address the crisis are unlikely to gain traction without addressing barriers posed by invasion denialism, competition for attention with connected issues such as human rights and climate, and conflicts of interest posed by economic constraints. There are also important constraints posed by the nature of the policy cycle and policy makers, who are essentially scientific amateurs suffering, like academics, from administrative overload. Policy makers are further beholden to political realities posed by public perceptions of the problem. Advocates of invasive species policy reform should therefore engage debates while emphasizing evidence that the problem is a serious threat, shifting the conversation away from a question of what the problem is, and focusing it squarely on discussion of solutions to address it. It is also essential that as advocates of reform, scientists succeed in clearly and carefully communicating risk and uncertainty and in unambiguously defining the difference between invasive and exotic species.

As a wicked problem, the forest health crisis is also dynamic. There are no one-size-fits-all solutions. Instead, the social challenges to adopting sensible forest biosecurity policy are unique in different contexts. Economic, social, political, cultural, and geographic constraints narrow the range of feasible policy outcomes across the world. To make matters even more wicked, the problem is embedded with other, interconnected crises, including economic and environmental inequity—people who rely more directly on forest resources bare disproportionate costs from forest loss—and environmental degradation, forest fragmentation, and climate change, which increase the susceptibility of forests to pest invasions and outbreaks. Finally, and perhaps most wickedly of all, implementation of solutions will reveal new problems due to conflicts of interest. These conflicts of interest consistently delay action, with dramatically negative outcomes, as exemplified by the loss of red-bay forests to laurel wilt (caused by *Raffalea lauricola*). As a direct consequence of failure to take early, decisive, and organized action, the avocado industry in Florida has already lost 600 ha, or nearly one quarter of its producing land area, and US$56 million to LWD since 2011.

We argue for forest biosecurity policy reform and a change in policy stance from one emphasizing reactive responses toward focus on proactive approaches. However, political and economic barriers combined with a lack of accountability currently limit implementation of prevention-based strategies. Costs of noncompliance suffered by importing countries are not shared by the exporters of pests in international shipments. Mistrust among trade partners combined with the low risk of being caught creates a “prisoner’s dilemma”. International trade partners and private stakeholders are reticent to bear the opportunity costs associated with strengthening international trade regulations even though such costs are much smaller than the damage to forests, the loss of the essential services they provide, or the associated downstream costs to society that will result from failure to act. The current lack of urgency in adopting and implementing stronger rules suggests that the high nonmarket value of forests is undervalued. To remedy this, progress could be made in the interim by sanctioning of repeat offenders.

We propose a proactive framework for action that includes: pre-invasion risk assessment that accounts for the high nonmarket value of forests and more completely accounts for the costs of potential losses; greater capacity for early detection, including through technologies such as remote sensing and rapid detection; legal and economic facilitation of rapid response worldwide; increasing forest resilience through conservation and sustainable land and forest use; and host resistance breeding. Importantly, an effective strategy is also needed for guiding land manager decision-making with respect to invasive species. Through long-term efforts to win incremental victories, the paradigm of what is possible may shift forest health biosecurity, the state of forest resources, and the societies that depend on them to an alternative and more resilient stable state.

C – Open Session 3

Moderator: Bill Riel[a]
[a] Canadian Forest Service

Impacts of mountain pine beetle outbreaks on the structure and composition of, and snag longevity in, lodgepole pine forests

Jackson P. Audley[a], Christopher J. Fettig[a], A. Steven Munson[b], Justin B. Runyon[c], Leif A. Mortenson[d], Brytten E. Steed[e], Kenneth E. Gibson[e], Carl L. Jørgensen[f], Stephen R. McKelvey[a], Joel D. McMillin[g], and Jose F. Negrón[h]
[a] Pacific Southwest Research Station, USDA Forest Service, Davis, CA
[b] Forest Health Protection, USDA Forest Service, Ogden, UT
[c] Rocky Mountain Research Station, USDA Forest Service, Bozeman, MT
[d] Pacific Southwest Research Station, USDA Forest Service, Placerville, CA
[e] Forest Health Protection, USDA Forest Service, Missoula, MT
[f] Forest Health Protection, USDA Forest Service, Boise, ID
[g] Forest Health Protection, USDA Forest Service, Flagstaff, AZ
[h] Rocky Mountain Research Station, USDA Forest Service, Fort Collins, CO

Mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae), is the most important forest insect pest in western North America and has impacted > 27 million ha of forests since 2000 (Fettig et al. 2020). Following historic mountain pine beetle outbreaks in the Intermountain West, U.S. from 2004-2012 (Figure 1), we investigated resulting tree mortality and the effects on forest structure and composition. Mountain pine beetle activity generated a substantial increase in the number of snags on the landscape (Audley et al. 2020). Snags are important components of forest ecosystems (Bull et al. 1997) but also pose a safety hazard to foresters, wildland firefighters, and recreationists (Guyon et al. 2017). We investigated the dynamics of beetle-killed lodgepole pine snags and identified factors contributing to snag fall.

A network of 125, 0.081-ha circular plots was established in lodgepole pine, *Pinus contorta*, forests in Colorado, Idaho, Montana, Utah, and Wyoming. Plots were installed in 2010 and sampled annually through 2019. We modeled snag fall rates using a Cox's proportional hazard model to estimate retention time and identify factors contributing to snag fall. For complete details of methods and sampling protocols, see Audley et al. (2020) and Audley et al. (2021).

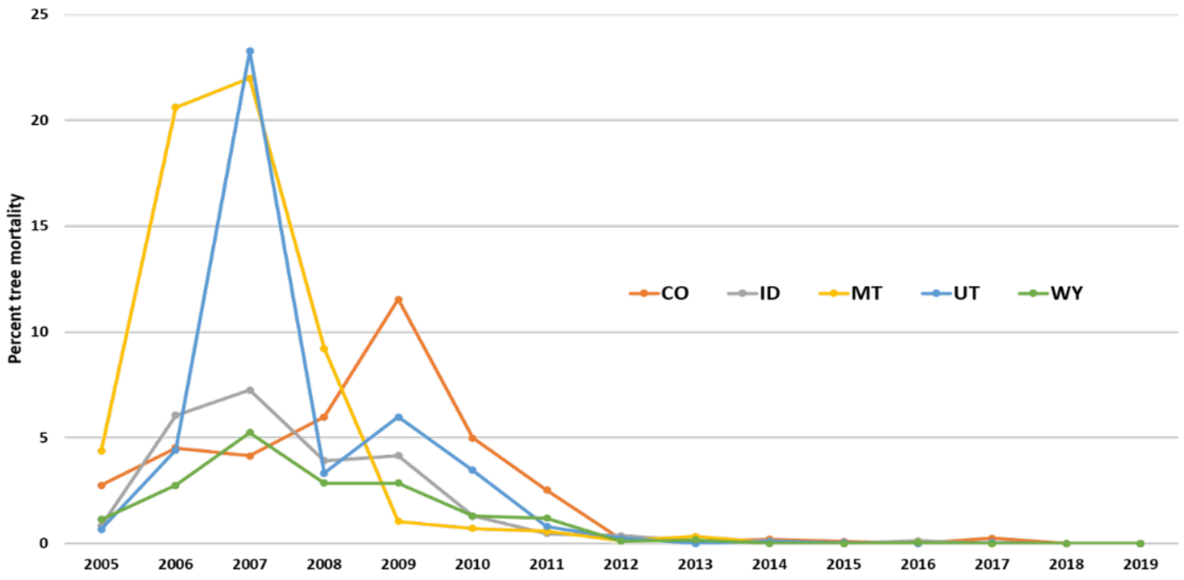

Figure 1. Mean percent of pines killed following mountain pine beetle outbreaks in Colorado, Idaho, Montana, Utah, and Wyoming, U.S., 2005-2019.

Five thousand one hundred and seven trees died across the network, 98.6% of which were lodgepole pine. Most of the observed tree mortality (68.8%) was attributed solely to *D. ponderosae*. Resulting mortality significantly reduced mean diameters at breast height (dbh) by 5.3%, quadratic mean diameter by 8.6%, tree height by 15.9%, number of live trees by 40.8%, basal area by 52.9% (Figure 2), and stand density index by 51.8%. Tree density significantly declined for all diameter classes (5-cm classes) except for the smallest class (7.5-12.5 cm). Subalpine fir, *Abies lasiocarpa*, was well represented in the understory regeneration. We observed more *A. lasiocarpa* than *P. contorta* seedlings (≤0.3 m tall) in all states except Montana. An increased number of *A. lasiocarpa* saplings (>0.3 m tall and <7.6 cm dbh) contributed to the increase in the number of saplings observed across all states from 2010 to 2018. The number of snags (standing dead trees) increased substantially (by 1324.7%). Interestingly, 75.3% of snags remained standing in 2019 (Figure 3), prompting an interest in understanding snag longevity. Our model predicted a half-life of 16 years for lodgepole pines killed by *D. ponderosae*. Northern facing aspect was the most significant factor in prolonging snag retention. Snag height was also positively correlated with longer retention times except when a snag had a greater height to diameter ratios (i.e., tall with small dbh). Implications of these results were discussed.

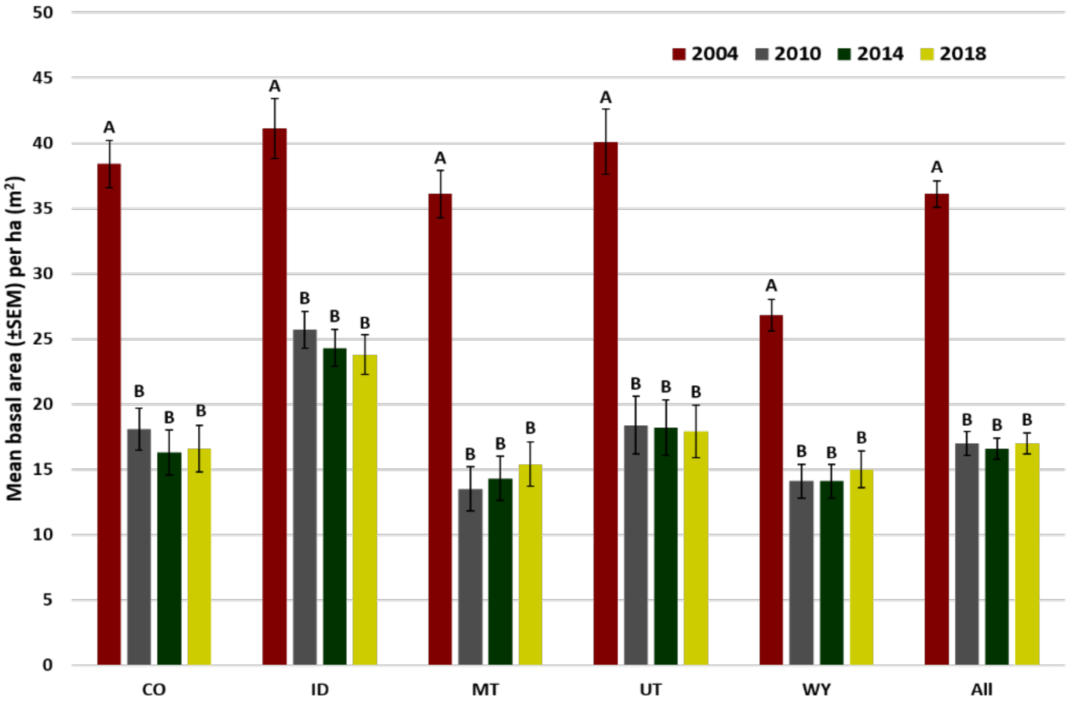

Figure 2. Mean basal area of live trees (m^2 per ha ± SEM) by state in 2004, 2010, 2014, and 2018. Means were compared within each state and not among states. Different letters indicate significantly different means ($P \leq 0.05$).

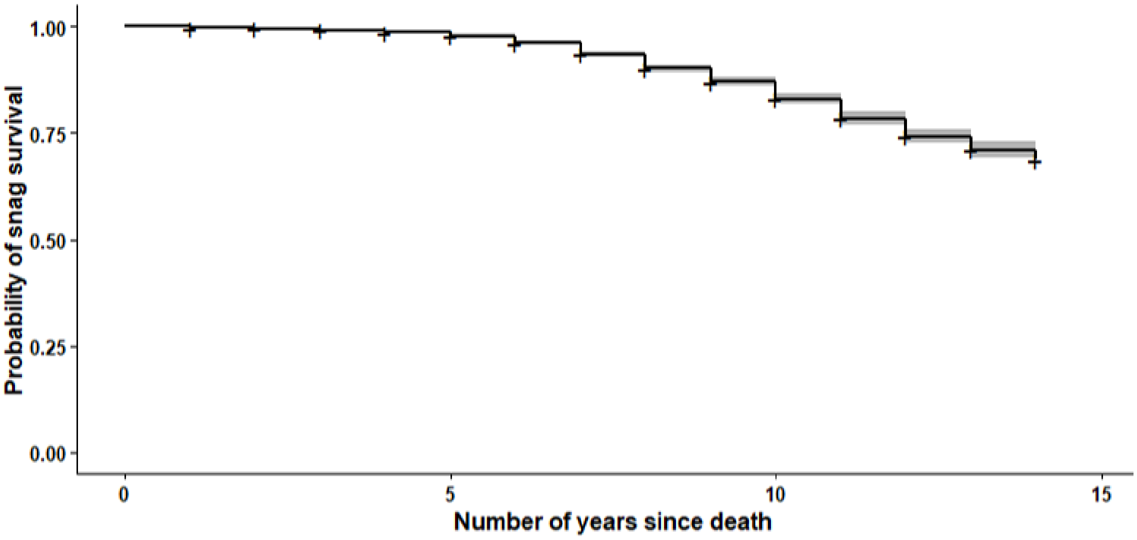

Figure 3. Survival function from Cox's proportional-hazards model describing the probability that lodgepole snags remain standing (i.e., "survive") based on individual snag and plot level characteristics. Modeling was done using the coxph() function in the survival package with R statistical software (3.6.3) in RStudio (1.2.5033).

Keywords: forest disturbance, forest change, tree mortality, lumber salvage, snag fall

Acknowledgements: We thank D. Grosman (Arborjet Inc.); D. Claessen (Big Horn National Forest, USDA Forest Service); R. Davy (Bridger-Teton National Forest, USDA Forest Service); P. Foulk (Eldorado National Forest, USDA Forest Service); D. Balthrop, C. Beebee, K. Bedford, D. Blackford, A. Boyce, M. Casey, R. Cruz, V. DeBlander, L. Dunning, A. Guinta, J. Guyon, R. Halsey, C. Hayes, E. Hebertson, L. Lowrey, R. Mendoza, B. Meyerson, P. Mocettini, J. Neumann, D. Ott, D. Reboletti, A. Sills and C. Toone (Forest Health Protection, USDA Forest Service); H. Delb (Forest Research Institute of Baden-Württemberg); Montana Conservation Corps staff; C. Delphia (Montana State University); J. DeVillier and M. Barrett (Pacific Northwest Research Station, USDA Forest Service); C. Dabney, H. Fettig, R. Gerrard, S. Hamud and A. Morris (Pacific Southwest Research Station, USDA Forest Service); W. Dunning, L. Huckaby, J. Mercado, J. Popp and J. Trilling (Rocky Mountain Research Station, USDA Forest Service); and R. Progar (Sustainable Forest Management Research, USDA Forest Service) for technical assistance. In addition, we thank the Arapaho-Roosevelt, Beaverhead-Deerlodge, Boise, Bridger-Teton, Salmon-Challis, and Uinta-Wasatch-Cache National Forests and Grand Teton National Park for their support and for providing access to study sites. This research was funded, in part, by USDA Forest Service Forest Health Monitoring Evaluation Monitoring grants (INT-EM-F-10-03, INT-EM-F-14-01 and INT-EM-17-01 to the Pacific Southwest Research Station) and Forest Health Protection Regions 1 & 4.

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Elongate hemlock scale in Michigan: initial assessment of distribution, impacts, and natural enemies

Toby R. Petrice[a], Therese M. Poland[a], and F. William Ravlin[b]
[a] USDA Forest Service, Northern Research Station, Lansing, MI
[b] Department of Entomology, Michigan State University, East Lansing, MI

Introduction

Elongate hemlock scale (EHS), *Fiorinia externa* Ferris (Hemiptera: Diaspididae), is an invasive pest of hemlock (*Tsuga* spp.) that was introduced into the eastern U.S. from Japan in the early 1900s (Ferris, 1942). Recently (ca. 2010), EHS was discovered in Michigan on hemlock trees along the shoreline of Lake Michigan. In southern Lower Michigan, eastern hemlock (*Tsuga canadensis*) is primarily restricted to the shoreline of Lake Michigan, while in northern Lower and Upper Michigan, eastern hemlock is more widely distributed. A few years prior to the discovery of EHS in Michigan, hemlock woolly adelgid (HWA), *Adelges tsugae* Annand (Hemiptera: Adelgidae), was discovered in the same region of Michigan (Limbu et al., 2018). State of Michigan employees and local resource managers are currently applying insecticide treatments and implementing quarantine restrictions in efforts to eradicate HWA.

EHS feeding often causes needle chlorosis and premature needle drop, which weakens trees and may result in tree mortality if heavy infestations persist for several years (Danoff-Burg & Bird, 2002; McClure, 1980; Stimmel, 1980). In addition to hemlock, EHS attacks several other North American conifers (Dale et al., 2020; McClure & Fergione, 1977; Stimmel, 1980). However, except for damage to Fraser fir (*A. fraseri*) Christmas trees, the impacts of EHS on additional North American conifers has received limited attention (Douglass & Davidson, 2005).

Female EHS pass through three developmental instars (i.e., crawler/1st instar, 2nd instar, and mature female) before mating and producing eggs, while males pass through four instars (i.e., crawler/1st instar, 2nd instar, pupa, adult) before emerging as winged adults and mating. In the eastern U.S., most crawlers are present in spring; however, developmental stages tend to overlap with most life stages present throughout the growing season (Stimmel, 1980). The parasitoid, *Encarsia citrina* Crawford (Hymenoptera: Aphelinidae), is the primary natural enemy of EHS in the U.S. (Abell & Van Driesche, 2012; McClure, 1977, 1979).

Although EHS is not considered an aggressive hemlock pest relative to HWA in the eastern U.S., there is concern regarding impacts that EHS may have on eastern hemlocks and other conifer hosts in the Upper Midwest. Moreover, EHS is frequently intercepted on freshly cut Fraser fir Christmas trees imported into Great Lakes region annually. In 2020, we initiated studies in Michigan to determine: 1) the distribution and impacts of EHS on eastern hemlock and other host species (e.g., *Picea* and *Abies*) and 2) the presence and impacts of natural enemies on EHS. Study sites were selected that were free of HWA, given Michigan's current strategy of applying systemic insecticides to all HWA infested trees. Here we present preliminary data collected in 2020 from two sites with high populations of EHS in Michigan.

Methods

During August-November 2020, we conducted studies at two sites where EHS is established in southwest Michigan. At each site, we established 2-3 plots to evaluate and monitor EHS density, phenology, impacts, and natural enemies. Approximately every two weeks, four branch samples were collected from the lower canopy (ca. 1.5–2.5 m) of each of three eastern hemlock trees within each plot. Branch samples were also collected at 6.5–7.5 m canopy height from a subset of trees to compare for within-tree variation in scale density. In the laboratory, we counted the number of EHS scales and the number of needles with chlorotic tissue per 100 needles on current and previous year needles, and the mean current year shoot growth. We also counted the number and fate (i.e., alive, dead, parasitized, or predated) of each scale life stage present for the first 25 scales encountered on current- and previous-year needles for each shoot. To survey for EHS predators, we collected beat-sheet samples from trees within each plot on three occasions during September and November 2020.

We compared preliminary data on the effects of scale density on shoot growth and needle chlorosis using linear regression. The percentages of each scale life stage/fate were summarized across both sites.

Results

EHS was present on almost all trees at each site and scale densities on individual trees ranged from a high of 182 scales/100 needles to a low of 2 scales/100 needles. EHS was not recovered from non-hemlock hosts (*Picea* spp. or *Abies* spp.) Preliminary results showed a significant correlation with scale density and percentage of current- (P = 0 .00006) and previous-year (P = 0.00001) needles with chlorosis. However, no significant correlations were found between current-year shoot growth and scale density on current- (P = 0.0632) or previous-year (P = 0.3990) needles among hemlock trees. Preliminary results also showed a trend for higher scale densities at 1.5–2.5 m tree canopy height compared to 6.5–7.5 m. Most live EHS entered winter as adult females with or without eggs, followed by settled first instars; however, all life stages overwintered and could be found on needles at any given time from August–November.

The scale parasitoid, *Encarsia citrina*, was recovered from both sites with overall parasitism of 2nd and 3rd instar EHS averaging 44 % over all sample periods combined. We also recovered the scale picnic beetle, *Cybocephalus nipponicus* (Endrödy-Younga) (Coleoptera: Cybocephalidae), from beat sheet samples at both sites.

Summary

Although EHS densities appeared high on some trees and percentages of chlorotic needles were strongly correlated with scale densities, preliminary data did not show a significant correlation with reduction in current year shoot lengths and scale densities. This may be in part due to EHS concentrated in the lower canopy of hemlock trees. Most EHS entered winter as mature females or settled 1st instars; EHS appears to have a similar asynchronous development as reported in the eastern U.S. *Encarsia citrina* was common at both sites and parasitism averaged 44%. *Cybocephalus nipponicus*, an introduced scale predator from Southeast Asia, was the most abundant EHS predator recovered at both sites and was not previously known to occur in Michigan. Although the number of trees sampled to date has been limited, EHS was not found on other conifers species. We plan to continue sampling at the current sites during 2021 and expand our study area into northern Lower Michigan where EHS establishment overlaps with balsam fir (*Abies balsamea*), a reported host of EHS.

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Why isn't hemlock woolly adelgid killing trees in its native range? The role of insect predators in managing hemlock woolly adelgid

Ryan S. Crandall[a], Joseph S. Elkinton[a], and Jeffrey A. Lombardo[a]
[a] University of Massachusetts, Amherst

For decades, hemlock woolly adelgid (HWA), *Adelges tsugae*, has devastated hemlocks (*Tsuga* spp.) in the eastern United States. Fortunately, the HWA biological control program has successfully established predatory beetle *Laricobius nigrinus* at many sites in the eastern U.S. However, recent studies have shown that although *L. nigrinus* exerts significant predation rates on the HWA spring generation, overall densities of HWA were not reduced. To better understand host tree and natural enemy influences on HWA populations in its native range, we conducted a predator exclusion study at the Washington Park Arboretum in Seattle, Washington. Using native western hemlock (*Tsuga heterophylla*), as well as plantings of mature eastern hemlock (*Tsuga canadensis*), we tested the effects of predation, as well as tree species, on the survival of HWA cohorts experimentally inoculated on pairs of branches. Predators were excluded on one branch of each pair with mesh bags. In both rounds of experiment, after successful inoculation of equivalent densities of HWA spring generation on both pairs of branches, we found that western HWA settled preferentially on western hemlock and that insect predators were responsible for significantly reducing and maintaining low densities of HWA on branches without bags. Round two results suggest that summer-active predators were responsible for significant reduction of the HWA spring generation. Our results demonstrate the importance of summer-active predator acting on the spring generation in reducing HWA densities. We also found that tree resistance did not play a significant role suppressing HWA densities as shown by HWA readily colonizing western hemlock.

Formation of stable hybrid zone between the invasive winter moth and the native Bruce spanworm in eastern North America

Jeremy C. Andersen[b], Nathan P. Havill[a], and Joseph S. Elkinton[b]
[b] University of Massachusetts Amherst
[a] USDA Forest Service, NRS

Winter moth (*Operophtera brumata*) is a non-native invasive species that causes widespread defoliation to a number of forest, ornamental, and orchard tree and shrub species. Beginning in 2007, we established a transect along Route 2 in Massachusetts and in 2016 we established a transect along Route 1 in Connecticut in an effort to: 1) document the westward spread of winter moth into the interior portions of New England, 2) examine the presence of a hybrid zone, and 3) identify abiotic factors associated with the spread of winter moth. Along our Route 2 transect, the leading edge of the winter moth invasion (i.e., where 10% of individuals were estimated to be winter moth) expanded at a rate of 5.48 ± 3.75 km/year while the core population (i.e., where 90% of individuals were estimated to be winter moth) moved 1.40 ± 3.48 km/year during that same period. In contrast, along Route 1 in Connecticut the leading

edge retreated 14.7 km while the core population expanded 18 km in the three years of study. Along both transects we documented extremely high levels of hybridization with an average observed hybridization rate of 5.9 ± 0.7% across Route 2 and 4.9 ± 1.9% across Route 1. Our results indicate that while dynamic in nature, winter moth continues to spread westward into the interior portions of New England and that it has the potential become an important defoliator across much of the northeastern United States. Our documentation of a stable hybrid zone with high levels of genomic interchange between winter moth and Bruce spanworm suggests that the introgression of adaptive alleles is occurring, though what effect this has on the pest status of each species remains to be seen.

Abnormally high rainfall may cause regional hemlock woolly adelgid decline in the northeastern U.S.

Jennifer L. Chandler[a], Joseph S. Elkinton[b], and David A. Orwig[c]
[a] University of Massachusetts, Amherst
[b] USDA Forest Service, NRS
[c] Harvard University, Petersham, MA

The exotic invasive forest pest, hemlock woolly adelgid (HWA; *Adelges tsugae*) is the cause of widespread hemlock (*Tsuga* spp.) mortality throughout the eastern United States. Since its arrival in the northeastern U.S. in the 1980's, HWA has steadily spread throughout eastern hemlock (*T. canadensis*) stands. However, in 2018, anecdotal evidence suggested a sharp, widespread HWA decline in the northeastern U.S following a summer of heavy rainfall. To quantify this decline in HWA density and investigate its cause, we re-surveyed HWA in hemlock stands along a long-term HWA-monitoring transect from northern Massachusetts to southern Connecticut. As previous research documented presence of native fungal entomopathogens on HWA in New England and rainfall is known to facilitate the propagation and spread of fungus, we hypothesized that heavy rainfall may facilitate fungal infection of estivating nymphs of the sistens generation leading to a decline in HWA density. We tested this hypothesis by applying a rain-simulation treatment to hemlock branches with existing HWA infestations in western MA. Our results indicate a regional-scale decline and subsequent rebound in HWA density that correlates with rainfall at each site. Experimental rain treatments led to higher proportions of diseased and dead estivating nymphs compared to controls. This observational and experimental evidence of a rainfall-mediated HWA decline, in conjunction with no evidence for increased winter mortality, implicate heavy rainfall as the cause of the regional-scale drop in HWA density. Isolation of the fungal pathogen(s) responsible for this HWA mortality is underway and may lead to identification of novel biocontrol agents.

Emerald ash borer adult feeding preferences and larval performance on susceptible and "lingering" ash tree selections

Therese M. Poland[a], Jennifer L. Koch[b], Kathleen Knight[b], David W. Carey[b], Mary E. Mason[b], and Toby R. Petrice[a]

[a] USDA Forest Service Northern Research Station, Lansing, MI
[b] USDA Forest Service Northern Research Station, Delaware, OH

Introduction

The emerald ash borer (EAB), *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), a wood-boring beetle native to Asia, is the most damaging invasive forest insect pest to have invaded North America (Herms and McCullough 2014). It was likely introduced in the mid-1990s (Siegert et al. 2014), but was not discovered until 2002 near Detroit, Michigan (Haack et al. 2002; Poland and McCullough 2006). In EAB's native range in far eastern Russia, northern China, Japan, and Korea, it is generally only a pest of non-native ash or indigenous ash species (*Fraxinus* spp.) that are stressed by other factors (Yu, 1992; Liu et al. 2003; Zhao et al., 2005; Baranchikov et al., 2008; Duan et al. 2012; Haack et al. 2015). The situation in North America is quite different where EAB has spread to 35 states and 5 Canadian provinces as of June 2021. It has killed hundreds of millions of ash trees in urban and natural forests and threatens the entire ash resource, which is comprised of 16 known species (EAB Info 2021).

In forest monitoring plots, a small number of mature ash trees survived the initial killing wave of EAB, although some were attacked by EAB (Knight et al. 2012). The original ash population of 11,000 trees in the monitoring plots was reduced to 2.6% of trees surviving with only 1% having healthy crowns by 2012, two years after the ash mortality reached 95% (Knight et al. 2012). These surviving trees are referred to as "lingering ash" because, although they may simply represent the tail end of the mortality curve and still go on to die, they may also be rare ash tree phenotypes that make them less preferred by EAB or more resilient to EAB attack (Koch et al. 2015). There are multiple points of interaction between the EAB and its ash host including adults landing and feeding on leaves, females ovipositing on the main bole, and larvae tunneling through the outer bark into the phloem, cambium, and outer xylem. Differences in insect and host responses at one or more point(s) of the host-insect interaction may contribute to host resistance in synergistic ways and may be important in different genotypes or species or at different pest densities. Breeding to increase and combine these different mechanisms may lead to improvements in host resistance. Our objectives were to identify lingering ash trees and propagate them to evaluate emerald ash borer adult landing and feeding preferences and larval development and survival to identify trees with these different resistance mechanisms that can be used as parent trees in a breeding program. Further, we assessed the utility of a breeding program for the production of seed sources improved for EAB-resistance by examining resistance of trees produced from crosses of parent trees.

Methods

After the discovery of EAB in North America, we established long-term forest monitoring plots in Ohio and southeast Michigan to facilitate the search and discovery of ash trees that survived or "lingered" the invasion and establishment of EAB. Individual "lingering" green ash trees were selected for propagation and further evaluation that were $\geq$10-cm DBH, had healthy canopies, and survived for two or more years after EAB-caused stand mortality exceeded 95%. EAB adult host choice and feeding preferences were compared for subsets of select lingering ash trees in multiple-choice experiments using cut leaves in screen cages or two-choice experiments using sleeve cages on pairs of live potted trees in a greenhouse or using cut leaves in clear plastic boxes. We also compared larval weight, developmental stage, and larval survival by affixing EAB eggs onto grafted ramets of "lingering" ash selections and susceptible controls. The trees were dissected 8 weeks after estimated EAB-egg hatch, and the fate of each larva was scored as: 1) killed by tree (gallery ended, filled with callous or brown tissue, remains of larva not always discernable), 2) unrecovered (larva not found), or 3) live by larval instar (L1, L2, L3, and L4).

Results

Adult host preference and feeding bioassays compared new "lingering" ash selections PE41, PE56, PE62, PE65, PE73, PE75, with PE15 (lingering ash selection previously reported to be less preferred by adults in Koch et al. 2015), the EAB-susceptible green ash cultivar 'Summit' and PE37 (selected as an EAB-susceptible tree from a natural forest) in different experiments. Overall, across all experiments and bioassay types, leaves from PE15, PE41, and PE62 consistently had the fewest adult EAB observed per leaf per observation period, while leaves from 'Summit', PE37, and PE73 had higher numbers of EAB observed per leaf. Similarly, adult EAB consumed less foliage from PE15, PE41, PE56 and 'Summit' than from PE37 and PE73 cultivars.

The mean proportion of EAB larvae killed by ash host varied across grafted "lingering" green ash selections and ranged from 1% to 46%, while the proportion of host-killed larvae in the EAB-resistant cultivar 'Mancana' of the Asian species *Fraxinus mandshurica* was ca. 80%. In second generation crosses, the frequency of seedlings with host-killed larvae greater than 46% was higher overall relative to the original selections of lingering ash and was higher for families where both parents were "lingering" ash than for families with one susceptible parent. Larval mortality levels up to 90% were observed in some individual seedlings, indicating that breeding can produce populations improved for the larval kill trait. Field trials have been installed in Ohio to assess long-term field performance and correlation of EAB-resistance with bioassay results.

Summary

Our results demonstrate that some "lingering" ash selections were significantly less preferred for feeding by EAB adults, including PE15 a selection that was also less preferred in previous experiments (Koch et al. 2015). EAB-susceptible genotypes 'Summit' and PE37 had significantly higher numbers of beetles observed per leaf as expected, but less foliage was consumed from 'Summit,' which could indicate that 'Summit' may have higher nutritional value to EAB, thus requiring less consumption as nutritional balance and defensive compounds may influence insect feeding and longevity (Chen and Poland 2010). Several "lingering" ash selections displayed resistance to EAB through reduced larval weight, delayed larval development, and/or higher proportions of host-killed larvae. These measurable phenotypes likely explain why some ash genotypes have survived EAB attack longer than the majority of their counterparts and suggest that more than one resistance mechanism may be responsible. Field trials of clonal replicates of "lingering" ash genotypes and seedling families were planted to assess field performance. Overall, these studies indicate that a breeding program has the potential to generate seed improved for EAB resistance, which could be appropriate for ash restoration plantings.

Acknowledgments: This research was supported by funding from the USDA Forest Service Special Technology Development Program, USDA Animal and Plant Health Inspection Service, Pennsylvania Department of Conservation and Natural Resources, and Michigan Invasive Species Grant Program. We appreciate the help of numerous assistants in the lab and field including Aletta Doran, Julia Wolf, Jarrod Sanchez, Gavin Nupp, Miranda McKibben, Charlie Flower, Rachel Kappler, Brian Hoven, Timothy Fox, Mike Martinson, Minali Bhatt, Josie Griffith, Thomas Paul, and Joseph McCreary.

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Spread and phenology of *Spathius galinae* Belokobylskij & Strazenac (Hymenoptera: Braconidae) and *Tetrastichus planipennisi* Yang (Hymenoptera: Eulophidae), introduced parasitoids of *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae)

Nicole F. Quinn[a], J.S. Gould[b], Claire E. Rutledge[a], Joseph S. Elkinton[c], and Jian J. Duan[a]
[a] USDA Agricultural Research Service BIIRU
[b] USDA APHIS-PPQ, Buzzards Bay, MA
[c] University of Massachusetts

Agrilus planipennis Fairmaire (Coleoptera: Buprestidae), or emerald ash borer is an invasive wood-boring pest of ash trees (*Fraxinus* spp.) in the US. It is responsible for catastrophic decline of ash in urban and forested ecosystems, resulting in millions of dollars in injury and losses. Biological control is thought to be one of the most promising management options available to reduce *A. planipennis* spread and impact. To this end, from 2015 to 2017 two larval parasitoids of *A. planipennis* from its native range, *Spathius galinae* Belokobylskij & Strazenac (Hymenoptera: Braconidae) and *Tetrastichus planipennisi* Yang (Hymenoptera: Eulophidae), were released in wooded areas in New York and Connecticut. The purpose of this study was to measure the long-term spread and phenology of the released parasitoids. From May to September 2020, sentinel ash logs containing EAB larvae were deployed in naturally occurring *A. planipennis*-infested trees at each release site. Additional logs were deployed in 2 km intervals up to 14 km away from the release site. Logs were replaced every two weeks and the parasitization rate was recorded. Each month, three trees from each release area were cut and debarked to record *A. planipennis* infestation levels, natural parasitization rates, and *A. planipennis* and parasitoid phenology. We observed that both *S. galinae* and *T. planipennisi* emerged from the first replicate of logs deployed from the end of May to early June as far as 12 km away from the release site. Parasitization peaked in July and August, with sentinel logs deployed at each distance producing both species throughout the summer until mid-September. Both *S. galinae* and *T. planipennisi* were collected 14 km away from the release sites, the greatest distance away from the release sites sampled. Debarked trees produced similar findings, with relatively more immature specimens of both parasitoids collected in May and June, while adults and cocoons were relatively more frequently observed in samples collected from July and August. Our results indicate that the classical biological control program initiated several years ago has successfully produced a self-sustaining population of both *S. galinae* and *T. planipennisi*. Additionally, our results suggest that these parasitoids are capable

of spreading relatively quickly. This can be used to inform future release efforts, allowing for strategic spacing of release points across geographic regions. Overall, our study suggests that both *S. galinae* and *T. planipennisi* may continue to spread, increasing the biological control of *A. planipennis* over time across spatial scales.

The role of native natural enemies in the successful biological control of winter moth in the northeastern United States

Hannah J. Broadley[a], Joseph S. Elkinton[b], and George H. Boettner[b]
[a] USDA APHIS PPQ S&T Forest Pest Methods Laboratory
[b] University of Massachusetts

Winter moth, *Operophtera brumata*, a polyphagous caterpillar was accidentally introduced to the northeastern United States in the 1990s. Previous invasions of winter moth in Canada were successfully suppressed by the introduction of a parasitic fly, *Cyzenis albicans* from winter moth's native range. We established *C. albicans* at sites across the northeastern U.S. and establishment has coincided with a dramatic decrease in winter moth density. However, this success likely depends on additional mortality from native natural enemies including predators and parasitoids. In the native range of Europe, pupal predators were found to regulate winter moth densities. Further, in the two invasive populations of winter moth in Canada, predation was found to increase following the introduction of the biocontrol agents. We built on this earlier research and, over five field seasons, deployed winter moth sentinel pupae in the field to determine rates of predation and parasitism across a range of winter moth pupae and *C. albicans* puparia densities. Mortality on the pupae was high across sites and years (85 to 95%) and is primarilly caused by a diverse community of generalist ground predators. In years when winter moth densities were high prior to the establishment of *C. albicans* we did not observe density dependent mortality. Since 2016 however, *C. albicans* has become widely established and winter moth densities have decreased to a level comparable to what was found it its native range. And we have found that mortality on the pupae was density dependent and thus may stabilize winter moth at low density. Overall, our research shows that mortality on winter moth pupae was already high in the northeast but that the introduced biocontrol agent provides enough additional mortality to render winter moth a non-pest.

CONCURRENT SESSION 4

A – When do old plays work & when do we need to rewrite them? Part 2

Moderators: Sandy Smith[a] and Chris J.K. MacQuarrie[b]
[a] University of Toronto John H. Daniels Faculty of Architecture, Landscape and Design, Graduate Department of Forestry
[b] Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre

The legacy of managing mountain pine beetle in British Columbia: the science and the policy

Lorraine E. Maclauchlan[a]
[a] Ministry of Forests Lands and Natural Resource Operations and Rural Development, British Columbia Provincial Government, Thompson Okanagan Region

Abstract

British Columbia's pine forests have experienced many large-scale mountain pine beetle, *Dendroctonus ponderosae* Hopkins, outbreaks that have resulted in the mortality of hundreds of millions of trees over expansive areas of forest. In response to these landscape-level events, foresters and scientists have developed a suite of management strategies and tactics to mitigate the impacts of mountain pine beetle (MPB). When major infestations of both spruce beetle, *Dendroctonus rufipennis* (Kirby), and MPB erupted in central B.C. in the 1970's and 1980's, the B.C. government developed a coordinated response, which resulted in the creation of the Pest Management Program (now Forest Health); and, so began the battle of the beetles in B.C. With the most recent and largest MPB outbreak on record developing in north central British Columbia during the 1990's, federal and provincial governments once again looked to their top scientists for guidance to undertake this monumental challenge. In this presentation, I will describe intervention techniques used to control MPB, and B.C.'s current strategies that incorporate new technology, modelling, harvesting and scientific insight. I will also highlight the never-ending challenges faced by forest managers in B.C. who must contend with the sheer physical scale of the province, climate change and biological, social and political intricacies. However, perhaps the most pressing questions may be: "what have we learned and how will our future management of MPB differ"?

Background

British Columbia has an area of almost 95 million hectares (ha) (BC MSRM 2003), of which 62 million ha is coniferous forest, with pine being the most ubiquitous conifer (5 native pine species are found in B.C.: limber, lodgepole, western white, whitebark, and ponderosa). Of the total forested area in B.C., 46% contains some pine or host material for MPB.

Lodgepole pine comprises one quarter of the provincial timber supply; thus, the socioeconomic impacts of the most recent outbreak are enormous (Alfaro et al. 2010). Of the total pine volume in the province, approximately 1.9 billion m^3 is susceptible to MPB attack (older than 60 years and in climatically suitable biogeoclimatic zones) (Walton 2013).

The B.C. Ministry of Forests Lands and Natural Resource Operations and Rural Development, whose headquarters is based in Victoria, is divided into Forest Regions and Districts where day-to-day forest management activities are conducted. The Province has established designated Timber Supply Areas (TSAs) designed to practice sound, integrated, resource management that improves the allowable annual cut (AAC). TSAs were originally defined by an established pattern of wood flow from management units to the primary timber-using industries. They are the primary unit for AAC determination.

In B.C., bark beetles, including MPB, periodically reach outbreak levels, threatening sustainable forest management across a wide variety of ecosystems. B.C. has a long and complex history of MPB outbreaks and its management. Today, MPB has shaped the current forested landscape in B.C., and thus dictates how we must plan our forestry activities going forward. These outbreaks raise the question: “does beetle suppression work”?

MPB outbreak history in B.C.

MPB outbreaks have been recorded since the 1920’s and 1930’s in B.C. Early outbreaks were documented primarily from ground observations and minimal air surveys, and were mapped in the Chilcotin plateau, as well as west-central B.C. In the 1940’s, significant MPB-caused mortality was recorded in southeast B.C., with smaller infestations in western white pine recorded in the Shuswap and coastal B.C. The 1950’s through 1960’s saw one of the longest outbreaks ever recorded (18 years) in north-central B.C., with smaller outbreaks in coastal B.C. Aerial mapping greatly improved during this time. Until the late 1970’s, lodgepole pine was not a desirable commercial species and little action was taken to address these outbreaks. The Province contained large, remote, inaccessible expanses of lodgepole pine and therefore, any management efforts were conducted near existing mills and communities, using clearcut harvest to extract beetle-infested timber; with some limited fall and burn and single-tree extraction. During this time, there was also a large outbreak of spruce beetle. These two concurrent outbreaks prompted the B.C. Government to create a Pest Management Program, which would address future bark beetle outbreaks. Up to this point, there was a massive array of good science on these bark beetles, but limited technology and harvest capabilities.

In the 1980’s to early 1990’s (Figure 1) another extensive MPB outbreak occurred throughout the Chilcotin plateau and southeastern B.C., with most of the outbreak remaining remote and inaccessible. The Pest Management Program expanded, with entomologists, pathologists and technicians positioned in all Forest Regions and many Districts. The 1980’s outbreak saw the use of pheromones being widely implemented for single-tree treatments, targeted harvest of infested trees and grid-baiting blocks prior to harvest. The early version of the Shore-Safranyik hazard rating system (Shore and Safranyik 1992) was used to help identify priority areas for treatment and harvest. At the end of the outbreak, scientists (Drs. John Borden, Les Safranyik), forest practitioners (Government and industry) and other specialists formed a task force to develop scientifically-based strategies and tactics to address and manage future MPB outbreaks. The product of this task force was the document “Strategies and tactics for managing the mountain pine beetle, *Dendroctonus ponderosae*” (Maclauchlan and Brooks 1994). These strategies and tactics were later partially incorporated into the new Forest Practices Code (FPC) Act, enacted July 1995, and the FPC Bark Beetle Management Guidebook (B.C. Ministry of Forests 1995).

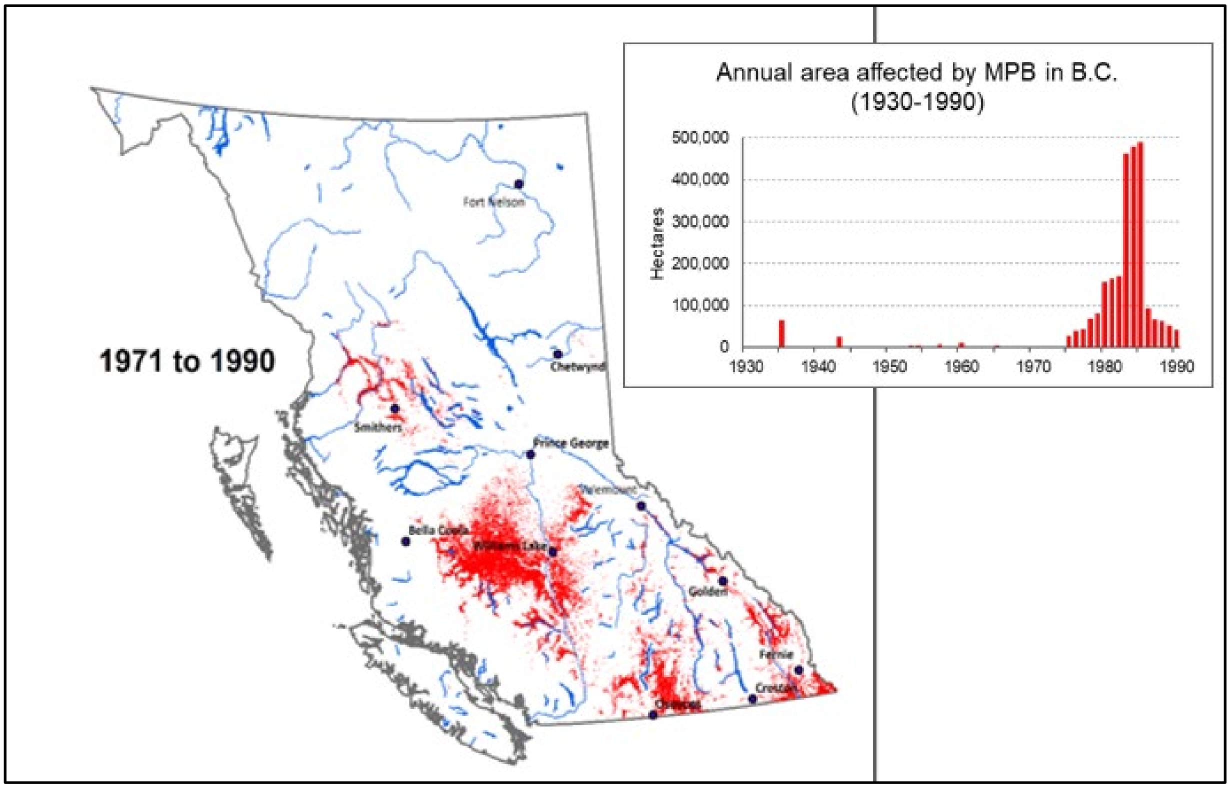

Figure 1. Map showing MPB attack (1971-1990) and a graph of annual attack from 1930 to 1990 in B.C.

The development and implementation of landscape-level long- and short-term strategies are the foundations of successful bark beetle management. Beetle Management Units (BMU) are the keystone of these strategies and are applied over designated geographic areas to identify areas where specific beetle management strategies can be applied. Management strategies (Table 1) are broad approaches that have specific objectives. Each strategy has an associated array of applicable tactics or treatments (Table 1). Treatments are applied to specific infestations or areas within a BMU to achieve the objective of the strategy. BMUs provide the basis for evaluating damage to timber, impact on other resources, effectiveness of treatment, and resource allocation and monitoring. BMU strategies must be incorporated into all higher-level planning processes. They cannot be considered in isolation as each management unit will impact the beetle situation of its neighbor. Therefore, the strategy selected for a BMU must be compatible with those taken in adjacent units and with the overall integrated resource use plans for the area.

Six strategies (Table 1) were defined to address bark beetle infestations. Selection of the relevant strategy is based on the amount of available host (pine) and extent and distribution of beetle infestations in an area. Strategy selection considers resource management objectives and the expected impact of the beetle in adjacent management areas. The selected strategy will define the most appropriate treatment combinations and the intensity and frequency of their application.

Table 1. List of strategies and tactics for MPB.

Strategies	Tactics
Prevention: Long-term (host management, species selection, hazard rating).	**Hazard & Risk Rating**
Suppression: Reduce populations by treating **>80%** of known infestations in each year.	**Survey & assessment**: Aerial overview surveys and detailed aerial surveys
Maintain Low: Applicable in chronically infested stand and manageable within the AAC. Harvest is concentrated on current attack.	**Ground detection**: Locates current attack; assesses merchantability (size/volume, green-red-gray ratio) and operability/access
Holding: Applicable in chronically infested stands but contains some larger inaccessible infestations. Harvest is still concentrated on current attack.	**Single-tree treatments**: Small scale harvest; fall & burn; MSMA (no longer in use); heli-logging; semiochemicals (grid-baiting, spot baiting)
Salvage: Value (fibre) recovery is the highest priority. Harvest dead trees prior to significant degradation (shelf life)	**Harvest priority rating**
Monitor / Abandon: No control. Track and record attack level	**Hauling restrictions**
	Access development
	Beetle-proofing
	Silviculture/regeneration

That brings us to the most recent 1990's to 2015 MPB outbreak in B.C. Beetle populations built up throughout the interior, from north central B.C. to the south and southeast of the province. A severe drought in 1998 "kick-started" the outbreak and massive expansions were recorded until its collapse in 2015. This outbreak was the largest on record and ultimately the result of extensive, contiguous areas of mature to over-mature lodgepole pine and climate change (Carroll et al. 2003).

The cumulative area in B.C that was at least somewhat affected by this outbreak is estimated at 18.3 million hectares and approximately 731 million m^3 (54%) of B.C.'s merchantable pine volume has likely been killed (Figure 2). We witnessed range expansion of MPB to the most northern areas of B.C., into higher elevation forests and eastward over the Rocky Mountains into Alberta. The amount of mortality caused by this MPB outbreak put extreme pressure on B.C.'s mid- and long-term timber supply due to AAC uplifts and accelerated harvest. It has also caused regeneration backlogs and the largest silviculture programs in B.C.'s history.

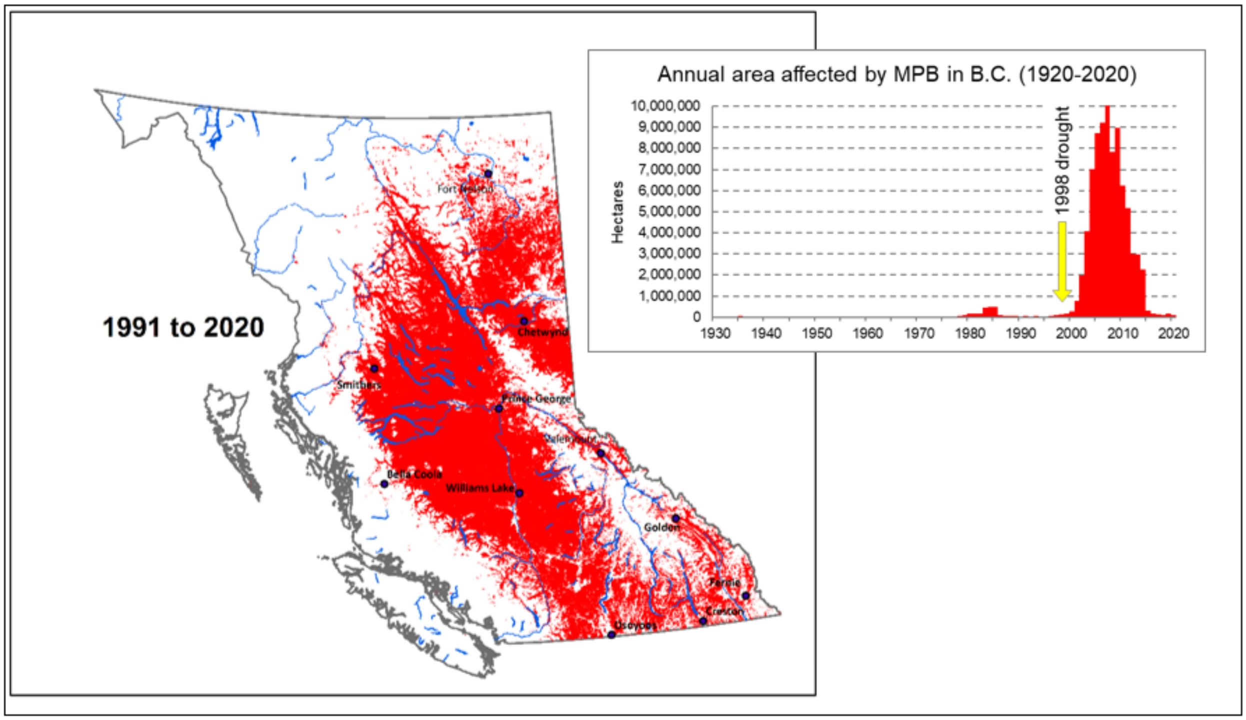

Figure 2. Map showing MPB attack (1991-2020) and a graph of annual MPB attack from 1930 to 2020 in B.C.

Response to the 2000's MPB outbreak and lessons learned

During the building and expansion phase of this outbreak, B.C. underwent significant changes in its laws governing forest practices. In April 1991, the Forest Resources Commission of B.C. recommended a "single, all-encompassing code of forest practices" be developed and implemented. On June 15, 1995, the **Forest Practices Code (FPC) of British Columbia Act** and **Regulations** came into effect. The FPC was very prescriptive and rule-based and did not necessarily accommodate the quick, proactive and reactive responses necessary for managing such an explosive and massive insect outbreak. Because of public pressure to move from management for volume, to management for values, in 2004 there was another change in law. The **Forest and Range Practices Act** and **Regulations** came into effect focusing on professional reliance, with an emphasis on better managing for water, wildlife, biodiversity, cultural values, and non-timber forest resources. As government, industry, communities and others were navigating these regulatory changes, the MPB kept sweeping through B.C.'s forests (Figure 3).

Figure 3. MPB attack in the Quesnel TSA (2006).

During the course of the most recent outbreak, lodgepole pine went from being a relatively undesirable commercial species to being declared the province's most important, producing more than $7 billion in forest products each year (CLMA/NFPA Mountain Pine Beetle Emergency Task Force 2000). Both government and industry task forces were established to battle the MPB epidemic and salvage attacked timber. A provincial "Beetle Boss" (coordinator) was appointed to help create and oversee bark beetle management efforts and enact the Bark Beetle Regulation (BC MOF 2001). Under this regulation, the coordinator could designate an area as an emergency management unit to aggressively apply treatments, which could help mitigate/control the MPB. Together, government and the forest industry endeavored to focus efforts on managing MPB in high priority green attack areas; mitigate impacts on timber supply; and, implement community economic diversification options unrelated to timber supply.

Another strategic document, the Mountain Pine Beetle Action Plan 2006-2011 (BC MOFR 2006), guided provincial response and helped coordinate all those working to mitigate the beetle's devastation: government, communities, First Nations, industry and other stakeholders. This action plan addressed forestry and environmental issues, as well as economic, social and cultural sustainability. This initiative realized that mitigation would be an ongoing process, requiring two or perhaps three decades to complete. It provided a high-level framework to direct provincial ministries and assist coordination between governments, industries and stakeholders over a set timeframe.

On the science and modelling side, researchers provided invaluable tools and information that guided the provincial response to the MPB epidemic. Riel et al. (2003) developed a model (known as SELES-MPB) capable of projecting MPB spread and impacts on the landscape through time and space, which was relied upon by B.C.'s Chief Forester and other managers to explore and evaluate potential management strategies. This model also projected stand level impacts (e.g., trees and volumes killed by diameter class, resulting stand structure), increasing its utility as a decision support tool. There was much advancement in the understanding of the impacts of climate change on range expansion and forest carbon feedback (Carroll et al. 2003; Safranyik and Carroll 2006; Kurz et al. 2008; Safranyik et al. 2010), numerous studies on the shelf-life of MPB-killed trees (Lewis and Thompson 2011), hydrology (Redding et al. 2008), post-harvest recovery and the impact of MPB attacking young stands (Maclauchlan 2006, 2008; Maclauchlan et al. 2015). Lodgepole pine that was regenerated following the MPB outbreak of the 1970's and 1980's was now being attacked by MPB (Figure 4). Huge silviculture programs were initiated in the 2000's to address mortality in young stands: start over or leave?

Figure 4. Young lodgepole pine stands attacked by MPB; left Kamloops TSA and right Quesnel TSA.

Many factors influenced the last MPB outbreak including:

- age and abundance of pine on the landscape;
- climate (1998 drought, lack of cold winters, moderating summer temperatures);
- a delayed or varied harvest response in some areas of the province;
- changing legislation in B.C.; and,
- MPB build-up in non-timber harvest land base (e.g. Parks, inoperable land).

The question remains, does beetle suppression work? I maintain that the answer is "Yes". However, more importantly the question should be: "When does Suppression work, for how long and where"? Keys to successful Suppression must include:

- a coordinated approach over the entire affected and at-risk landscape;
- implementation of appropriate strategies (including suppression) and being nimble in your response to building and changing MPB scenarios;
- implementation of the tools at-hand in a logical and effective manner;
- acting early in the outbreak cycle and rapidly - targeted, pro-active approach is imperative;
- access management; and,
- always considering the long-term impact on forest landscapes, ecosystem functions, and reforestation.

Over 50 years of excellent science has proven that the concept of beetle management is straightforward; it is the implementation which is complex. Some tough lessons learned: know when and where to give up on Suppression and switch to other strategies to extend live timber supply and ecosystem values and functioning. Although a variety of silvicultural tools and management strategies can be used to minimize timber losses to mountain pine beetle (Safranyik et al. 1974; McMullen et al.1986; Shore and Safranyik 1992; Maclauchlan and Brooks 1994), effective control programs require early detection, rapid implementation, and continuous commitment.

The impediments to Suppression include:

- politics;
- budgets, staffing, training;
- lumber markets; and,
- at more local scales, a lack of trained personnel, and appropriate harvesting options.

Critical aspects for achieving effective beetle Suppression include:

- strong and informed leadership and strategic planning;
- BMUs correctly designated and re-assessed annually;
- annual, precise geospatial information (location, severity, extent of MPB);
- priority areas delineated, ranked and assigned actions; and,
- aggressive, rapid response in real time.

Some critical lessons learned:

- predicting the progression of the infestation is difficult;
- predicting shelf-life is difficult (±15 years);
- there are always green trees cut when salvage harvesting;
- AAC uplifts can be both positive and negative;
- AAC uplifts create tenure challenges;
- licensee harvest needs to be focused; and,
- community leaders need to be briefed often.

MPB-attacked forests are undergoing substantial conversion. Although lodgepole pine is still the most dominant species in the interior of B.C., there is a shift to regenerating mixed species stands that include many shade-tolerant species. Shade-tolerant subalpine fir and interior spruce are the most dominant understory species that are regenerating below dead, MPB-killed canopies, followed by low-to-moderate shade-tolerant species such as lodgepole pine and Douglas-fir. We have learned that many heavily impacted stands that were left intact and not harvested after being killed by MPB are regenerating well and indications are that there is sufficient stocking of healthy trees (Hawkins et al. 2012). Stands in the north are regenerating better than those in the south of the province.

In conclusion, scientists continue to inform forest managers about emerging science and technology that should be incorporated into policies for managing our forest resource. With our rapidly changing climate and increasingly large insect outbreaks, we must have detailed discussions of what has been learned from past MPB outbreaks in order to better address those that will undoubtedly arise in the future.

Keywords: mountain pine beetle outbreak, British Columbia, management strategies

Acknowledgements: British Columbia Forest Health Group, Peter Hall (retired Provincial Entomologist), Janice Hodge (JCH Forest Pest Mgmt.), Albert Nussbaum (Director, Forest Analysis and Inventory Branch, FLNRORD), and Julie Brooks (Forest Health Mgmt.).

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How have phytosanitary approaches to address forest-product pest management changed?

Meghan Noseworthy[a]

[a] Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre

Abstract

In the past, pest mitigation of forest products has relied mainly on fumigation and heat treatments to reduce pest risk. A wider variety of options are available today, including systems approaches, new methods for applying heat treatment, and lower dosages of both fumigants and heat. Changes in approaches to forest-product pest management are guided by International and Regional Standards for Phytosanitary Measures. Standards provide guidelines for adoption of new treatments and options available for appropriate pest risk reduction measures, with the ultimate goal of protecting forests by reducing the movement of plant pests.

Overview

Globalization has led to increases in both plant pest movement and scientific research on methods to reduce the risk of pest movement on international trade pathways. Knowledge of how insects behave in novel habitats and by what pathways they reach new habitats, combined with their biology and phenology, helps to develop risk models. This information forms the basis for the development of phytosanitary approaches to reduce the risk of pest movement and in turn to protect forests globally.

The term “phytosanitary” literally translates to “plant health”. Phytosanitary approaches or measures refer to requirements imposed to maintain the health of plants. Forestry phytosanitary research focuses on forest pests (e.g. insects, nematodes, vertebrates, fungi or fungal-like organisms) moving on forest products (e.g. live plants, plant parts, roundwood and sawnwood, wood chips, solid wood packaging). As a means to reduce the risk of pest movement on forest and plant products, the global Sanitary and Phytosanitary (SPS) Agreement was proposed. As part of the World Trade Organization (WTO) - SPS Agreement, the International Plant Protection Convention (IPPC) helps nations around the world work together to promote trade while preventing the introduction and spread of exotic pests. Currently 184 contracting parties are signatory to the IPPC and cooperate by developing International Standards for Phytosanitary Measures (ISPMs); guidelines for conducting safe trade in a fair and transparent way.

International Standards for Phytosanitary Measures provide guidelines, using harmonized language and internationally accepted definitions for use in the development of import requirements, which protect plants. For example, ISPM 5, Glossary of phytosanitary terms (IPPC Secretariat, 2021) defines terms for use in the creation of international trade agreements. Different ISPMs provide guidance on how to analyze pest risk, develop certification systems and eradication programs, and conduct pest reporting and inspection. Some ISPMs are product- or treatment-specific, while other standards address options for reducing the risk of pests moving in horticulture on wood or on used vehicles and machinery. Each standard outlines its scope, addresses a major issue, and provides guidelines on how to approach the issue, with options for measures that can be applied when incorporated into agreements. ISPMs are under constant review and are periodically revised as new information and technology becomes available. As a result of their standardized and comprehensive format, the 45 ISPMs developed to date have been instrumental in the development of safe trade initiatives.

Existing phytosanitary measures described in ISPMs and specifically targeting wood products and the movement of wood pests, include heat treatment and fumigation (ISPM 15, 28, 39; IPPC Secretariat 2019a, 2016, 2020). Different methods for applying both measures have been developed over the past 70 years, including conventional heat treatment and moisture reduction in kilns, joule heating (successfully implemented today as a low energy and low cost heat alternative), and dielectric heating (NAPPO, 2014). Fumigant treatments such as methyl bromide and phosphine have recently been reassessed or phased out due to harmful environmental or human health effects (Bersi, 2010), in parallel with the development of improvements in fumigant administration, application of lower effective dosages, improvement of recapture systems, and assessment of new prospective fumigants (e.g. ethanedinitrile, EDN). Other measures include silvicultural practices to promote healthy forests such as thinning, removal of infested trees, and planting forests with mixed species to improve biodiversity and reduce forest pest vulnerability. Combined with surveillance and monitoring for pests, these measures can be used to develop pest-free areas.

The process for acceptance of a new treatment is outlined in the treatment standard, ISPM 28. Specific treatments for regulated pests are also outlined in this document, and currently include sulfuryl fluoride fumigation treatment for insects and nematodes in debarked wood, cold treatments, vapour heat treatments and irradiation treatments (IPPC Secretariat, 2016).

Systems approaches provide a comprehensive and logical option for addressing forest product pests. Based on a combination of best practices and HACCP (Hazard Analysis Critical Control Point) principles, each step represents an opportunity for applying one or more risk reduction measures. The combination of measures results in an overall lowered pest risk (IPPC Secretariat, 2019b). The benefit of using a systems approach is the availability of more options for risk reduction, which can be useful when other options are either not available, not economically feasible or not environmentally sound. In 2018, the North American Plant Protection Organization (NAPPO) adopted a regional standard (RSPM 41, NAPPO 2018), outlining how to design a forest products systems approach. The document presents options available at each step in a system, from planting genetically resistant seedlings through post-production processing. MacQuarrie et al. (2020) demonstrated the application of a systems approach to successfully reduce the phytosanitary risk posed by *Agrilus planipennis* Fairmaire in *Fraxinus* (ash) lumber.

Research to identify the lethal dose required to devitalize a variety of wood pests associated with wood products, is ongoing with researchers across the Canadian Forest Service. This work will support heat treatment schedules and provide evidence for lowering treatment temperatures resulting in positive environmental and economic effects. Decreased lethal fumigant levels have been quantified, where efficient recapture methods and efficacy data show that lower concentrations of fumigants are effective for devitalization of specific wood pests (Najar-Rodriquez et al., 2020).

Contaminating pests (hitchhikers) represent an important phytosanitary issue requiring further research. A few well-known examples of contaminating pests in North America are *Lycorma delicatula* (White), the spotted lanternfly, the *Lymantria dispar* complex, and *Halyomorpha halys* (Stål), brown marmorated stink bug. Contaminating pests provide a unique biosecurity challenge as they often move on pathways not associated with their host plants. For example, spotted lanternfly oviposit on a number of host and non-host substrates including stone (Liu 2019). Research on contaminating pests entails collecting and analyzing information on the pest guilds, pathways, perching substrates and behavioural biology. Collaboration between scientists, border control officials, and plant protection organizations, to collect and analyze these data will lead to practical measures that will limit the spread of contaminating organisms. A related area warranting more research is sea container design and cleanliness. NAPPO and IPPC have been addressing this issue for the past decade through the North American Sea Container Initiative (NAPPO, 2019) and Sea Container Task force (FAO, 2020), however more science-based approaches to reducing pest movement on this pathway are needed.

While many traditional, single-treatment phytosanitary approaches to reducing the risk of moving forest pests on forest products have been successful, new technology and knowledge provide a wider variety of options. These include, for example: systems approaches, traceability and pest pathway analysis, molecular techniques that can expose the behaviour or attributes of successful invading organisms, or the effects of phytosanitary treatments, and; climate change models that predict forest resiliency to pests. As global trade continues to increase, the movement of wood and tree pests on wood products and other commodities continues to challenge scientists and regulators. Fostering cooperation among scientists, regulators and industry partners in the development of pest risk reduction strategies, including sharing science and collaboratively developing science-based policy, is a logical approach to promoting safe trade of forest products and protecting forests.

Keywords: phytosanitary measures, standards, pathways

Acknowledgements: Leland Humble, Eric Allen, Gwylim Blackburn

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Entomology notes from a small island: impact & management of invasive forest pests in Britain

Daegan Inward[a]
[a] Forest Research, Alice Holt Lodge

The spread of invasive species by international trade is a global concern, and Great Britain's long trading history has provided a wealth of opportunity for the accidental (and deliberate) introduction of non-native organisms to its shores. Yet compared with continental Europe and North America, the impact of invasive forest insects in Britain has been relatively limited to date. This talk will explore key introductions and pest threats from recent years, what factors might be limiting more widespread damage, and whether this can help to direct horizon scanning and surveillance activities in an uncertain future.

Keywords: invasive species, pest management

B – Highlighting early career professionals in forest health

Moderators: Jess Hartshorn[a] and Molly Darr[a]
[a] Clemson University

The symposium will have broad interest in that the proposed speakers' areas of interest span climate change impacts on tree defenses to insects and pathogens, population genetics of pests in forests, social impacts of forest management, and impacts of invasive species.

Impacts of tree ontogeny and biotic stressors on the composition of secondary metabolites within the phloem tissue of two species of ash (Oleaceae: *Fraxinus*) in New Hampshire

Todd Johnson[a]
[a] University of New Hampshire, Department of Natural Resources and the Environment

Since its accidental introduction into North America three decades ago, the invasive emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) has spread rapidly throughout the United States and killed millions of ash trees (Oleaceae: *Fraxinus*). This has resulted in severe ecological damage to natural and managed forests and economic losses exceeding billions of dollars. While most North American ash that are attacked by *A. planipennis* die, there is increasing evidence that some trees have the capacity to resist the beetle for longer periods of time, or to avoid attack altogether. This pattern is exemplified in smaller diameter ash trees where *A. planipennis* experience reduced levels of larval survival relative to larger trees of the same species. Here we report on our ongoing study to understand how ontogeny influences the composition of constitutive secondary metabolites, and how artificial infestation by *A. planipennis* and application of the plant hormone methyl jasmonate may interact with ontogeny to alter these chemical profiles within the phloem of green (*Fraxinus pennsylvanica*) and white (*F. americana*) ash across four diameter classes. Preliminary analysis indicates that prior to induction, the composition of secondary metabolites is similar regardless of size class. After induction, there is a large divergence in the composition of secondary metabolites according to size class, which may reflect that defensive strategies of ash are age-dependent. This research will increase our understanding of defensive strategies of *Fraxinus*, informing horticultural or silvicultural strategies to maintain healthy ash in light of the current invasion by *A. planipennis*.

The value of hybrid and nonnative ash for the conservation of ash specialists in regions invaded by emerald ash borer

Kayla I. Perry[a], Christopher B. Riley[a,b], Fan Fan[a,c], James Radl[a], Mary M. Gardiner[a], and Daniel A. Herms[a,d]
[a] Department of Entomology, The Ohio State University
[b] Bartlett Tree Research Laboratories
[c] Hebei Agricultural University
[d] The Davey Tree Expert Company

Widespread mortality of native North American ash caused by emerald ash borer (EAB; *Agrilus planipennis* Fairmaire) threatens native arthropod biodiversity, including ash specialist herbivores. However, hybrid ash populations with resistance to EAB may serve a role in supporting threatened communities of arthropods in landscapes impacted by EAB. In this study, we investigated the hypothesis that a North American x Asian hybrid ash could serve as a refuge for North American arthropods in a common garden experiment by comparing native beetle communities and herbivory on North American green (*Fraxinus pennsylvanica*) and black ash (*Fraxinus nigra*), the Asian Manchurian ash (*Fraxinus mandshurica*), and the black x Manchurian hybrid 'Northern Treasure' ash. We found that ash specialists were rare among trees in the common garden, as we collected only four of the 14 beetle species known to occur in the region. Species richness and composition of herbivores, as well as levels of herbivory, were similar among ash taxa, and these patterns were driven by native generalists. The lack of ash specialists collected indicates that regions experiencing late stages of EAB-induced ash mortality may have missed the opportunity to conserve populations of native specialist herbivores with resistant hybrids. In order to maximize the conservation potential for native arthropod biodiversity, hybrid and/or nonnative ash must be preemptively planted before widespread EAB-induced ash mortality has occurred in the region. Conservation of native North America ash specialists should be prioritized in areas on the leading edge of expanding EAB populations.

What bugs trees: an interdisciplinary approach to evaluating insect disturbances in western North America

Jodi Axelson[a]
[a] Resource Practices Branch - FLNRORD

In western North America, disturbances impact thousands to millions of hectares of forests annually, and in many regions, insects are the leading cause. Forest insects can be characterized by their guilds, each leaving their own signature on tree growth, mortality, and ecological patterns and processes. Two insect guilds – bark beetles in the genus *Dendroctonus* and defoliators in the genus *Choristoneura* have extensive ranges throughout North America and in many systems result in significant damage. Bark beetles are tree killers and outbreaks result in large pulses of mortality of their hosts. Thus, outbreaks are a stand releasing disturbance at small spatial scales, and at large spatial scales can reorient successional trajectories across the landscape. Defoliators, on-the-other hand, rarely result in the death of their host, and instead

outbreaks result in stand-to-landscape scale suppression signals in the tree-ring record. Here, I evaluate the compositional and structural changes that resulted from extensive bark beetle outbreaks in mixed conifer forests of the Sierra Nevada in California during and after the 2012-16 drought. At the stand scale, I will explore how wood anatomical characteristics are modified by a chronic western spruce budworm outbreak in xeric Douglas-fir forests of southern British Columbia.

CONCURRENT SESSION 5

A – Macroscale drivers of forest insect dynamics: distributions, abundances, and impacts

Moderator: Sam Ward[a]
[a] Mississippi State University

This session will cover several different mechanisms by which native and non-native forest insects undergo large-scale shifts in their distributions and/or abundances. Presentations will focus on the drivers of invasions (arrival, establishment, and spread), range shifts, and outbreaks. Speakers will highlight the many contributions macroscale ecology (a growing subdiscipline in ecology) has already made to forest entomology and identify areas in which the diversity of technologies used in macroscale investigations (e.g., remotely sensed and other forms of big data) can be further leveraged and integrated to understand the dynamics of insect populations.

Exploiting species-habitat networks to improve wood-boring beetle surveillance in areas surrounding entry-points

Davide Rassati[a], Manuela Branco[b], Claudine Courtin[c], Massimo Faccoli[a], Nina Feddern[d], Emily Franzen[e], André Garcia[b], Martin Gossner[d], Mats Jonsell[f], Matteo Marchioro[a], Petr Martinek[g], Alain Roques[c], Jon Sweeney[h], Lorenzo Marini[a]
[a] Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padova, Viale dell'Università, 16 – 35020 Legnaro (Padova)
[b] Instituto Superior de Agronomia, Centro de Estudos Florestais Tapada da Ajuda, Universidade de Lisboa, 1349-017, Lisboa, Portugal
[c] Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE), UR 0633, Zoologie Forestière, 45075, Orléans, France
[d] Forest Entomology, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, Birmensdorf, Switzerland
[e] Department of Biology, Xavier University, Cincinnati, OH, USA
[f] Department of Entomology, SLU, Box 7044, SE 750 07 Uppsala, Sweden
[g] Department of Forest Protection and Wildlife Management, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic
[h] Natural Resources Canada, Canadian Forest Service - Atlantic Forestry Centre, 1350 Regent Street, Fredericton, New Brunswick E3C 2G6, Canada

Ever-increasing international trade along with ongoing changes in trade networks is causing an impressive number of forest insect introductions (Brockerhoff and Liebhold 2017). This trend is particularly evident for wood-boring Coleoptera, especially bark and ambrosia beetles, longhorn beetles, and jewel beetles (Haack 2001; Eyre and Haack 2017). These insects may be present in wood-packaging materials, timber, and plants for planting (Meurisse et al. 2019), and are difficult to detect by routine inspections as infested materials may show little or no sign of infestation (Humble 2010). Traps baited with attractive lures placed in and around entry points are commonly used to complement visual inspections and improve chances of intercepting incoming species soon after their arrival (Poland and Rassati 2019). New Zealand (Brockerhoff et al. 2006), Australia (Anderson et al. 2017), Austria (Hoch et al. 2020), Canada (CFIA 2017), Italy (Rassati et al. 2015), Great Britain (Inward 2020), France (Fan et al. 2019), and the United States (Rabaglia et al. 2019) are examples of countries that adopted or are currently adopting this approach. Besides the low cost and ease of use, baited traps benefit from recent advances in wood-boring beetle chemical ecology (Millar and Hanks 2017; Seybold and Fettig 2021) and our understanding of factors that affect trapping success (Allison and Redak 2017).

Nonetheless, it is still unclear which points of entry should be prioritized, which is the optimal position where traps should be set up in areas surrounding entry points, and how many traps should be used. Entry points can be surrounded by different types of landscape, i.e., urban-dominated, forest-dominated and mixed, and the selection of the entry points to prioritize, the position of baited traps, and the number of traps needed might change depending on the landscape composition. In order to investigate these patterns, we used black and green multi-funnel traps baited with a multi-lure blend (Fan et al. 2019) in areas surrounding 13 entry-points located in nine countries (France, Portugal, Italy, Sweden, Italy, USA, Canada, Switzerland and Czech Republic). At each site, sixteen traps were deployed in a grid of 2 x 2 km defined a priori, with one trap per each cell of the grid. Selected sites covered a gradient of forest cover (from urban-dominated to forest-dominated landscape). Traps were left in the field for 5 months and all trapped beetles were identified to species. Species-habitat networks (Marini et al. 2019) were used to link exotic species presence and landscape composition at different spatial scale (i.e., both among-sites and within-sites). A high number of exotic species were trapped both in forest-dominated and urban-dominated landscape, suggesting that entry points cannot be prioritized based on the type of landscape surrounding them. At the single site level, preliminary results suggest that baited traps should be set up in the forest patches present nearby the entry point both in urban-dominated and mixed landscape, as the latter patches are the habitat that exotic species tend to colonize first. These forest patches should be targeted irrespective of the distance from the entry point area. In forest-dominated landscape, instead, understanding which is the optimal position where to set up baited traps is more complicated as exotic species tend to randomly disperse in the landscape. Thus, more traps are needed in forest-dominated landscape than in urban-dominated or mixed landscape. This information can prove useful for improving efficacy of surveillance programs at both national and international level.

Keywords: baited traps, early-detection, exotic species, surveillance, wood-boring beetles

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Alien forest pest explorer: an online portal for exploring ranges of non-indigenous forest pests and the status of their host tree species

Randall S. Morin[a], Songlin Fei[b], Andrew M. Liebhold[c], and Susan J. Crocker[d]
[a] USDA Forest Service, Northern Research Station, York, PA
[b] Purdue University, Department of Forestry and Natural Resources, West Lafayette, IN
[c] USDA Forest Service, Northern Research Station, Morgantown, WV
[d] USDA Forest Service, Northern Research Station, St. Paul, MN

Abstract

Invasions of damaging non-native forest pests are known to affect growth and mortality of host trees. National forest inventory data collected by the US Forest Service's Forest Inventory and Analysis (FIA) program can be used to quantify the impact of these pest species on host tree abundance as well as host growth and mortality rates. The Alien Forest Pest Explorer (AFPE) has been revamped as a portal for the exploration of spatial data describing the ranges of known damaging non-indigenous forest pests established in the United States and the status and trends in their host tree species. The online, interactive tool includes dozens of forest insects and about 15 species of forest pathogens. This site can be used to view and download maps and pest alerts for each of the forest pests as well as statistics about their host tree species from regional FIA data. The AFPE was designed as a data resource for forest health specialists, foresters, and the public. The home page includes a data dashboard that allows for national/regional examination of the number of pest invaders and host tree densities that are at risk. Additionally, individual data dashboards for the most widely distributed and damaging pests provide for investigation of pest range spread, host tree abundance trends, and host tree growth and mortality statistics. Such results demonstrate how forest pest invasions can profoundly modify forest dynamic processes, resulting in long-term changes in forest ecosystems. URL - https://mapsweb.lib.purdue.edu/AFPE/.

Assessing drivers of local range expansion across the invasive range of a high-profile insect pest

Gabriela C. Nunez-Mir[a], Jonathan A. Walter[b], Kristine L. Grayson[c], and Derek M. Johnson[a]
[a] Department of Biology, Virginia Commonwealth University
[b] Department of Environmental Sciences, University of Virginia, Charlottesville, VA
[c] Department of Biology, University of Richmond, Richmond, VA

Background

Macroscale studies are able to produce useful insights for invasion management, particularly when localized information about the dynamics of specific invasive species is unavailable. Here, we present a macroscale study of the roles of invasion drivers on the local dynamics of a high-profile pest, *Lymantria dispar dispar* L., in order to exemplify the utility of macroscale and multi-scale research on science-based large-scale pest management. *Lymantria dispar* is a foliage-feeding insect that was introduced to North America in 1869, and is now established in

20 U.S. states and five Canadian provinces (Animal and Plant Health Inspection Service, 2019) causing widespread defoliation and other damaging impacts (USDA Forest Service, 2020). The management of *L. dispar* along the expanding population front is currently led by the National Gypsy Moth "Slow the Spread" program (STS). However, prioritization of problem areas remains a necessity, as the number of areas that need to be treated in a given year are often greater than what can practicably be managed (Tobin & Sharov, 2007).

Objectives

Although *L. dispar* is one of the most extensively documented invasive insects in North America, our understanding of the relative roles of environmental and anthropogenic factors on *L. dispar* spread at local scales, and how these roles change across the invasive range, is relatively limited. In this study, we seek to broaden our understanding of the effects of these drivers to be able to identify habitat characteristics that make certain areas vulnerable.

Methods

We assessed the relative effects of various anthropogenic and environmental variables on local diffusive spread rates of this high-profile pest across its invasive range in the United States. We applied a Bayesian probabilistic framework to annual *L. dispar* trap catch data from 1985 to 2015 in order to determine the probability of *L. dispar* establishment in 5 by 5 km quadrats. We then calculated the establishment rate of 8,010 quadrats by measuring the number of years from first detection of *L. dispar* to the year when probability of establishment was 99% or more in these quadrats. To assess the effects of environmental and anthropogenic variables on each quadrat's establishment rate, we performed linear mixed-effects regression models for three different sub-regions within the invasive range, plus a range-wide model.

Findings

We show that spatial trends of waiting times appear to be increasing across the leading edge, suggesting that local rates of establishment of *L. dispar* may be decelerating. Seasonal temperatures were found to be the primary drivers of local establishment rates across. Furthermore, the effects of some factors waiting times to establishment varied across sub-regions. Winter temperatures had the strongest effects, especially in the northern parts of the range. Our findings describe a hierarchy of factors that influence local range dynamics of a high-profile pest, and describe how these interactions change across the U.S. invasive range, highlighting the utility of macroscale studies.

Keywords: climate suitability, invasive spread, *Lymantria dispar*, large-scale management, pest management

Acknowledgements: We thank the Slow-the-Spread Program for access to *L. dispar* data and our funding source for this research, National Science Foundation Award (DEB-1556767).

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A review of forest disturbance attribution using remote sensing

Arjan J.H. Meddens[a], Amanda Stahl[a], and Robbie Andrus[a]
[a] School of the Environment, Washington State University, Pullman, WA

Ecological disturbances are an integral component of forest ecosystem dynamics. Remotely sensed data offer a spatially extensive and temporally consistent record over the past several decades (e.g., Landsat 1984 to present) for monitoring disturbances in forest ecosystems. Researchers have developed methods to successfully detect many types of abiotic and biotic disturbances that operate across a range of spatial and temporal scales during the last two decades. Many studies have highlighted that disturbances can be detected with relatively high levels of accuracy (~90%). Far fewer studies have demonstrated methods to accurately attribute detected disturbances to a specific disturbance type, and land managers need to know disturbance type to inform effects on forest dynamics. Our objective was to synthesize studies that report on (semi-) automated forest disturbance attribution using remotely sensed data and/or geospatial analysis. We report on the current state of algorithm development (i.e., methods), evaluation methods, and the accuracy of attribution by disturbance type. Finally, we make recommendations for future directions that will improve automated disturbance attribution.

Tree diversity and bark beetle outbreaks in subalpine forests of the Rocky Mountains

Sarah J. Hart[a]
[a] Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins

Coincident with recent warm and dry conditions, native bark beetles have killed conifer trees across 22.5 M hectares of forest in the western United States. In the Interior West, much of the tree mortality has been concentrated in subalpine forests, where the mountain pine beetle (MPB; *Dendroctonus ponderosae*), spruce beetle (SB; *D. rufipennis*), and western balsam bark beetle (WBBB; *Dryocoetes confusus*), have caused extensive mortality in lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*), respectively. Given these bark beetle species affect only one or several tree species, a common management goal to mitigate the effects is to promote species diversity. Yet, many stands are composed of a mix of pine, spruce, and fir and it remains poorly understood how tree species diversity affects tree survival in the face of multiple bark beetle outbreaks. Here, I use USFS Forest Inventory and Analysis (FIA) data to examine the effects of diversity on patterns of tree mortality due to MPB, SB, or WBBB activity across subalpine forests. I found the probability of either MPB, SB or WBBB occurring within a stand was greatest when all three hosts were present, but the severity of cumulative bark beetle activity was greatest when only one host was present. In stands with multiple hosts, the co-occurrence of multiple bark beetle species occurred infrequently (ca. 5% of plots), but generally resulted in higher severity infestation. These results highlight the importance of managing forests in the context of multiple bark beetle species.

A method for detecting fundamental changes in population dynamics across landscapes and over time

Devin W. Goodsman[a]
[a] Northern Forestry Centre 5320 122 Street Northwest Edmonton, Alberta, T6H 3S5

Background

Fundamental changes in insect populations manifest as changes in their spatiotemporal dynamics on the landscape. However, because many insects are capable of dispersing long distances, local changes in population dynamics do not necessarily reflect changes in local determinants of population growth. Nevertheless, it is theoretically possible to detect changes in the drivers insect populations based on fundamental shifts in the patterns of their population movement and abundance. This premise is a tenet in landscape ecology, in which spatial heterogeneity is related to ecological drivers.

Objective

Although there are currently methods for quantifying movement speed and direction (Bjornstad 2020), many of these approaches are based on the traveling wave paradigm (Kolmogorov 1937; Skellam 1951; Kot, Lewis, and Driessche 1996), which assumes a simple form of population movement away from a source. Methods such as these are useful for quantifying movement that is consistent across space rather than heterogeneous. Here I present a method that I developed for quantifying heterogeneous movement speeds and directions.

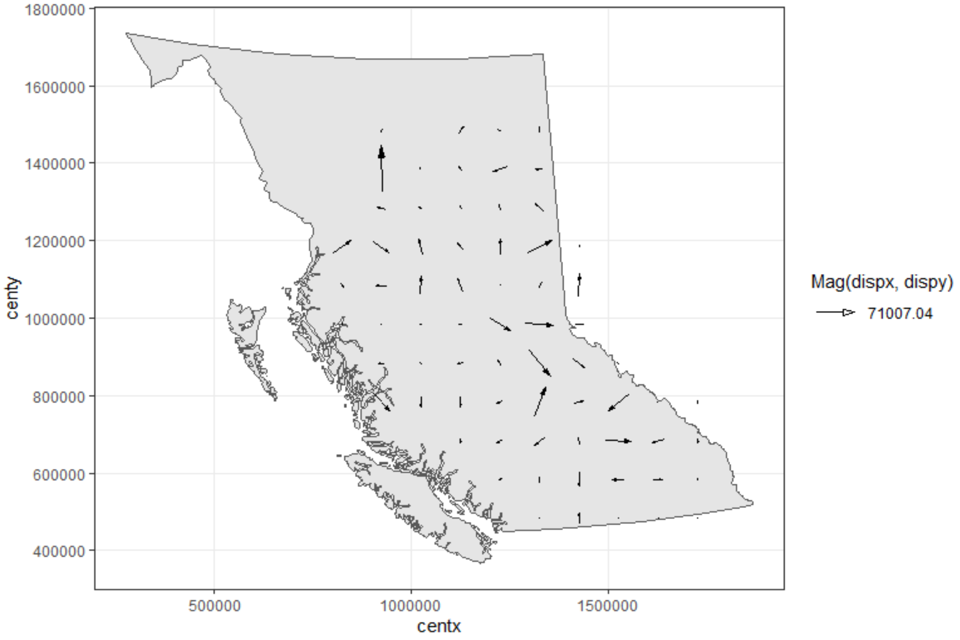
Methods

A manuscript that describes the mathematical and computational underpinnings of the method that I have developed is currently under review elsewhere and so in order to minimize overlap; I will focus on the application of the approach to illustrate complexity of population movement patterns in space. Because this work is under review elsewhere, I will provide only a brief description of the methodology. In my personal time, on weekends, and vacation days, I have developed software (Goodsman 2021) that estimates vector fields based on displacement in spatiotemporal data quantified using implementations and novel extensions of the Digital

Image Correlation approach (Anuta 1970; Sutton, Orteu, and Schreier 2009). The software is freely available for download and experimentation from CRAN and can be used within the R software environment (R Core Team 2021). I demonstrate the capabilities of the software by using it to analyze the spread patterns of the recent mountain pine beetle outbreak in British Columbia, Canada.

Findings

I apply my approach for quantifying heterogeneous movement of the mountain pine beetle outbreak in British Columbia, Canada. I focus my analysis on the years 2006 to 2011, which were years of severe infestation in the province, with northward and eastward population movement. Application of the computational approach in (Goodsman 2021) reveals complex and heterogeneous movement patterns (see figure below). From the image, northward and eastward movement are evident. However, the directions and magnitudes of movement are spatially variable, with the largest velocity vectors occurring at the outer edges of the vector field (see figure below). These movement patterns were not the same as those in the first years of the mountain pine beetle outbreak in British Columbia, and changes in patterns of movement imply changes in underlying population drivers. The drivers that influence the dynamics in the figure are currently under investigation in my laboratory. The approach developed here may be most useful for synoptic pattern analysis, hypothesis generation, and for analyses of the causes of population range expansion and contraction.



Acknowledgements: I am grateful to the British Columbia Ministry of Forests for their open data sharing approach. All of the data used in this short summary were derived from data are available at https://www.for.gov.bc.ca/ftp/HFP/external/!publish/Aerial_Overview/

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B – Caught in the middle: forest insect and disease challenges in Minnesota

Moderators: Brian Aukema[a] and Dora Mwangola[a]
[a] University of Minnesota

This session highlighted forest insect and disease challenges of relevance to Minnesota, the state that was expected to be the host before the meeting was converted to a virtual format due to the global pandemic. This session showcased how state, federal, and university partnerships engage to prioritize and confront forest health challenges whose impact reaches beyond the state's borders. This session highlighted basic, applied, and regulatory issues across several forest types in the Great Lakes region.

The Minnesota invasive terrestrial plant and pest center model

Robert C. Venette[a,b]*, Heather Koop[b], Christine Lee[b], and Amy Morey[b]
[a] USDA Forest Service, Northern Research Station, St. Paul, MN
[b] Minnesota Invasive Terrestrial Plants and Pests Center, University of Minnesota, St. Paul, MN

The Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC), established in 2014 at the University of Minnesota, has propelled research on invasive species that affect forests, prairies, wetlands, and agriculture. The Center has become a regional and national leader by adopting a unique operational model. MITPPC leads a rigorous, objective prioritization of the greatest terrestrial invasive species threats to the state; the prioritization drives an annual request for research proposals. Many forest pests are a high priority for their ecological and economic impacts. MITPPC draws expertise from the entire University of Minnesota system to build cross-disciplinary research teams to address these priorities; teams include external implementation partners to ensure that all research, even the most basic study, improves the management of invasive species. The Center also strongly encourages investments in graduate education. Lastly, MITPPC communicates findings to an engaged public through diverse outlets. This model has garnered more than $17 million in state support for more than 30 research projects involving 90 scientists. Funding primarily comes from the Environment and Natural Resources Trust Fund, as recommend by the Legislative-Citizen Commission on Minnesota Resources, with in-kind support from USDA Forest Service. The Center has sponsored novel research on gypsy moth, emerald ash borer, and mountain pine beetle among other species. MITPPC provides a unique organizational model for sustainable research to prevent or mitigate impacts from diverse invasive species threats.

The search for associational protection in urban forests treating for emerald ash borer

Dora Mwangola[a], Jennifer Burrington[b], Angie Ambourn[b], Mark Abrahamson[b], and Brian Aukema[a]
[a] Department of Entomology, University of Minnesota, St. Paul, MN
[b] Minnesota Department of Agriculture, St. Paul, MN

Emerald ash borer (EAB), *Agrilus plannipenis*, is an invasive wood boring insect that attacks, and kills ash trees (*Fraxinus* spp.). It was accidentally introduced to North America from Asia in the 1990s and since then it has spread to five Canadian provinces and 35 American states. The main control strategy in the urban ash populations is the use of systemic insecticide treatments, which can be costly when treating large numbers of trees. This study investigates whether associational protection can be conferred to untreated trees by treating a subset of a susceptible urban ash population. In 2017, approximately 100 trees were selected in 12 sites in Minnesota with known EAB infestation. We treated a subset of trees with emamectin benzoate in 8 sites and treated a subset of trees in the remaining 4 sites with azadirachtin. We have been monitoring tree crown health to determine whether associational protection is occurring at the sites and treating trees according to each insecticide's recommended regime. The main objective of this study is to develop a more cost effective and environmentally favorable treatment regime in urban centers.

Image analysis homes in on oak wilt pockets in Minnesota

Rachael Dube[a]
[a] Minnesota Department of Natural Resources

Oak wilt is a deadly disease that affects many species of oaks. Caused by a non-native, invasive fungus (*Bretziella fagacearum*), it is one of the most serious diseases of oak trees in the eastern US and threatens Canadian provinces. In Minnesota, oak wilt is present in the southern half of the range of northern red oak (*Quercus rubra*). The Minnesota Department of Natural Resources (DNR) uses annual aerial surveys and reports from citizens to detect oak wilt infestations. However, social distancing restrictions from the COVID-19 pandemic prevented aerial surveys in 2020. In lieu of aerial survey, the DNR conducted a desktop survey of oak wilt using color infrared images from the National Agriculture Imagery Program, searching over 4.3 million acres of imagery to identify visible damage from oak wilt. This method resulted in the detection of almost 11,600 oak wilt pockets, and was 11 times more effective at finding pockets than in a 2016 aerial survey. Through this project, we more thoroughly understand how much unmanaged oak wilt is present in Minnesota and have valuable information for strategic management. Though time-consuming relative to other forms of delineating forest damage, we find that mapping forest health damage on still imagery remains the most reliable, accurate, and precise method of estimating impacts across a large landscape from agents that kill patches of forest and persist on the landscape over years.

Resurgence of larch casebearer

Samuel Ward[a,b] and Brian Aukema[a]
[a] Department of Entomology, University of Minnesota, St. Paul, MN
[b] Mississippi State University

Larch casebearer (*Coleophora laricella*, Hübner; Lepidoptera: Coleophoridae) is a non-native defoliator of larches (*Larix* spp.) that established in North America in the late 1800s near Northampton, Massachusetts. The insect has been present in Minnesota for several decades and historically remained at endemic levels undetectable via aerial surveys. Casebearer populations had been maintained at low densities throughout the invaded range following the establishment of natural enemies imported from Europe. However, since 2000 and despite the persistence of imported natural enemies, aerial surveys in Minnesota have detected widespread outbreaks annually. We investigated casebearer responses to weather using several laboratory, field, and modeling approaches, finding that longer growing seasons and warmer autumns are likely driving the resurgence of casebearer in Minnesota. The importance of ongoing climate change for casebearer outbreaks, and the insect's interaction with native disturbance agents, was discussed.

Trichoferis campestris, a new exotic woodborer now found in Minnesota

Grace Haynes[a], Angie Ambourn[b], Marissa Streifel[c], and Brian Aukema[a]
[a] University of Minnesota
[b] Minnesota Department of Agriculture
[c] USFS State and Private, St. Paul, MN

Nonindigenous forest insects are frequently introduced to the United States via solid wood packing material often associated with international trade. Though it is rare for these insects to establish, those that do can negatively impact novel ecosystems. It can be difficult to predict future impact when an insect is first intercepted, so it is key to exploit initial windows of opportunity to learn as much about an introduced insect as possible. *Trichoferus campestris* (velvet longhorned beetle) was first intercepted in the United States in the 1990s and in Minnesota in 2010. It has established populations in at least three states. Reports from its native range in northeastern Asia suggests that this beetle can infest trees of a wide variety of genera, and even dead and dry wood. To date it has not caused notable impacts in North America, but little data exists on its behavior in its introduced range. In this study, we explored ovipositional preferences and larval performance of *T. campestris* on cut branches of four North American tree species found in the upper Midwest, including both healthy wood and wood exhibiting symptoms of disease. If management should become necessary, our data can inform strategies to control *T. campestris*.

The scale that stole Christmas

Angie Ambourn[a] and Steven Shimek[a],
[a] Minnesota Department of Agriculture

Elongate hemlock scale *Fiorina externa*, is a scale pest of over 43 species of trees, several of which are commonly grown for Christmas trees. This insect has become a complex issue for the Christmas tree growing industry in the Mid-Atlantic States. Elongate hemlock scale was first detected on wreaths and other evergreen decorative items in big box stores in 2018 and on trees being sold for home use in 2019 and 2020. In response to these finds, the state took several actions and conducted outreach to cities, municipalities, and homeowners on proper disposal of holiday greenery as part of our multifaceted response. The state of Minnesota imports many Christmas trees, wreaths and other holiday greenery items but we also have our own Christmas tree producing industry. Although this insect is not established in Minnesota, it remains unknown if this insect could establish here and what the potential impacts will be to our local Christmas tree growers. This talk highlighted the story of elongate hemlock scale in Minnesota from the first find to our state response and future directions.

C – When ‘native’ species have an ‘exotic’ response

Moderator: Tara Bal[a]

[a] College of Forest Resources and Environmental Science, Michigan Technological University

Challenges with new associations between organisms continue to emerge due to multiple factors. Significant ‘exotic’ damaging agents may no longer be coming from a different continent, but with climate change and anthropogenic change, novel encounters continue to occur, as endemic species respond via range expansion, population dynamics, trophic interaction shifts, or in other ways. Forest pest management has been increasingly balancing efforts between ‘exotic’ and ‘native’ pests, which poses additional challenges for the larger social and political landscape as we develop a better understanding of how species will respond, leading to decisions about how species interactions are mitigated.

This session highlights native species across multiple regions of North America and many long-term research efforts documenting novel behaviors. Management responses to these novel behaviors are context specific, but more often are becoming experimental themselves, blurring the lines between research and management. The necessary resources to support additional research for proactive measures and experimental mitigation strategies will not exist without strong input from stakeholders and policy makers. Continuing to monitor and conduct basic and applied research on native pests and promote rapid knowledge transfer or communication between and among professionals and the public remains key for overall forest health, especially in the realities of our current and future ecosystem conditions.

Eastern larch beetle: celebrating twenty years of outbreak (and counting)

Brian Aukema[a]

[a] Department of Entomology, University of Minnesota

The eastern larch beetle, *Dendroctonus simplex*, is found throughout the range of eastern larch or tamarack, *Larix laricina*. Native to North America, the insect typically colonizes weakened or downed tamarack but may kill live trees when populations build. Tree-killing outbreaks have historically not lasted more than two to five years. In the Great Lakes region, however, eastern larch beetle has been killing mature tamarack since 2001. In Minnesota, a 20-year outbreak now covers more than 500,000 acres of mature tamarack covertype in the northern part of the state. In this presentation, I summarized past research on correlates of the outbreak related to changing climatic conditions and preview the next steps we will be undertaking to understand the behavior of this system. These include elucidating a fuller understanding of the chemical ecology of eastern larch beetle and the associated complex of natural enemies.

Phenological synchrony between eastern spruce budworm and its host trees increases with warmer temperatures in the boreal forest

Deepa Pureswaran[a]
[a] Natural Resources Canada, Canadian Forest Service, Quebec

Phenological synchrony between herbivorous insects and their host trees is critical to insect performance in temperate climates with short growing seasons. Climate change is predicted to alter relationships between trophic levels by changing the phenology of interacting species. We tested whether synchrony between two critical phenological events, budburst of host species and larval emergence from diapause of eastern spruce budworm, increased at warmer temperatures in the boreal forest in northeastern Canada. Budburst was up to 4.6±0.7 days earlier in balsam fir and up to 2.8±0.8 days earlier in black spruce per degree increase in temperature, in naturally occurring microclimates. Larval emergence from diapause did not exhibit a similar response to increased microclimate temperature. Instead, larvae emerged once average ambient temperatures reached 10°C, regardless of differences in microclimate. Phenological synchrony (lag between onset of budburst and peak larval emergence) increased with warmer microclimates, tightening the relationship between spruce budworm and its host species. Synchrony increased by up to 4.5±0.7 days for balsam fir and up to 2.8±0.8 days for black spruce per degree increase in temperature. Our results suggest that under a warmer climate, defoliation would begin earlier in the season, potentially increasing damage on the primary host, balsam fir. Black spruce, a secondary host which escapes severe herbivory because of a two-week delay in budburst, would become more suitable as a resource to the spruce budworm. The northern boreal forest where black spruce dominates but balsam fir is a significant component could become more vulnerable to outbreaks in the future.

Drivers increasing ticks and tick-borne diseases in North America

Maria Diuk-Wasser[a]
[a] Department of Ecology, Evolution and Environmental Biology, Columbia University

Tick-borne diseases continue to emerge and geographically expand in North America and worldwide. Factors driving the spread of *Ixodes* spp., the vectors of Lyme disease and other 6 human pathogens in the US, include climate and land use changes, tick vector and host population growth, as well as changes in people's behaviors affecting exposure. Other expanding endemic tick vectors include the lone star tick, *Amblyomma americanum*, and the dog tick, *Dermacentor variabilis*. The longhorned tick, *Haemaphysalis longicornis*, has recently invaded North America and is a potential vector of human and livestock pathogens. I describe the patterns and drivers of emergence of these endemic and invasive ticks and discuss approaches to control or mitigate human health risks.

Southern pine beetle behavioral shifts through space and time

Stephen Clarke[a]

[a] Forest Health Protection, USDA Forest Service, Lufkin, TX

The southern pine beetle (SPB), *Dendroctonus frontalis* Zimmermann, typically forms expanding infestations with distinct areas with pines under attack known as spot heads. In large, unsuppressed infestations, the beetles may attack pines too small for brood survival and non-traditional hosts such as spruce or hemlock. As the range of SPB expands northward in the US, spot growth may not be as continuous or predictable as in the Southeast. Though SPB usually infests the tree bole, branches may be attacked in Mexico, Central America, and the NE US. Downed green pines and even stumps are occasionally attacked. Climate, competition, and population levels are among the factors influencing these unusual behaviors. Speciation could eventually occur should these behaviors persist over time.

Keywords: bark beetles, colonization, behavior

Acknowledgements: Thanks to Jim Meeker, Kevin Dodds, Joel McMillan, Monica Gaylord, and Michael Bohne for their input and photographs.

Long-term fate of the invasive mountain pine beetle in the western boreal forest

Allan L. Carroll[a] and Stanley W. Pokorny[a]
[a] Department of Forest & Conservation Sciences, University of British Columbia

Climate warming has been implicated in recent hyperepidemics by eruptive species capable of altering ecosystem processes in habitats outside their historic range. However, range expansion during epidemics may not result in long-term persistence in novel habitats if sub-outbreak (endemic) populations require niche conditions that are distinct from epidemic populations. Mountain pine beetle (*Dendroctonus ponderosae*), the most severe disturbance agent within the lodgepole pine (*Pinus contorta* var. *latifolia*) forests of western North America, recently breached the historic geoclimatic barrier of the Rocky Mountains and expanded its range into evolutionarily naïve lodgepole pine and jack pine (*Pinus banksiana*) habitats contiguous with the transcontinental boreal forest. In this study, we examined the potential for mountain pine beetles to naturalize in newly invaded pine habitats by quantifying biotic interactions known to affect endemic population dynamics (i.e., the endemic niche) in 16 pine stands along a transect from the native range to the eastern edge of the invasion front. We found that there was 3 times the density (trees/ha) of endemic-susceptible hosts (vigour-impaired trees as indicated by the presence of secondary bark beetle species) in native and naïve lodgepole pine habitats when compared with jack pine. The degree of inter-tree competition within a stand, which was generally low in jack pine, was found to be positively correlated with endemic-susceptible host abundance, and to be negatively correlated with tree size and growth rate. Additionally, subcortical competitor assemblages shifted from predominantly secondary bark beetles (Coleoptera: Curculionindae: Scolytinae) in the native range to woodboring beetles (Coleoptera: Cerambycidae) in jack pine. In newly invaded jack pine forests, 50% of endemic-susceptible trees were co-occupied by woodboring beetle species (*Tetropium* and *Monochamus* spp), whereas this was rare in native (ca. 0%) and naïve (20%) lodgepole pine forests. In the native

range, trees susceptible to endemic mountain pine beetles that were also infested by woodborers exhibited slightly higher (ca. 25%) phloem consumption than trees infested by bark beetles alone, but phloem consumption by woodborers in trees in newly invaded lodgepole and jack pine habitats was 6 and 17 times greater, respectively, than that associated with bark beetles only. Thus, the endemic niche in novel habitats, especially jack pine, was further constrained by greater exploitation and interference competition. Novel lodgepole pine habitats comprise equal, if not greater suitability to endemic populations; however, the niche available to endemic mountain pine beetle in jack pine forests appears to be rare and highly constrained by competitors suggesting that long-term persistence in western boreal jack pine is unlikely.

CONCURRENT SESSION 6

A – Status and Management of World Changing Invasive Forest Pests

Moderator: Scott Salom[a]
[a] Department of Entomology, Virginia Tech

Part of our changing world in forestry has been the devastation caused by non-native insects and plant pathogens. While there are literally hundreds of species that could be covered, five species, four of which have a long history of impacting our forest ecosystems and one more recent, are presented here in the context of: 1. Current spread, damage, and impacts; 2. Integrated efforts towards management; and 3. Predicting the aftermath of invasion and success in management. Each pest has had major investment in study, and as a result, demonstrate the challenges that are faced when non-natives flourish in North America attacking trees and other plants with little or no resistance to them. It is suggested that investment into the study and management of forest pests, whether native or non-native, requires urgency as we struggle to maintain healthy native forest ecosystems. Because of scheduling conflicts, the spotted lanternfly talk by Hoover et al., could not be given. But the abstract is included here nonetheless, as it is a species requiring urgent action and study that should be included in any discussion on invasive forest pests in 2021.

After more than 150 years gypsy moth still dominates forest pest management in the USA

Tom W. Coleman[a] and Robbie Flowers[b]
[a] USDA Forest Service, Forest Health Protection, Asheville, NC
[b] USDA Forest Service, Forest Health Protection, Bend, OR

Since the late 1860's, European gypsy moth continues to be a prominent threat to oak-dominated forests in the USA. Cyclical outbreaks continue to impact the eastern part of the country with recent outbreaks occurring in Connecticut, Massachusetts, and Rhode Island (2015 to 2018) and western Virginia (2016 to 2018). In recent years, populations have increased in Michigan and Pennsylvania, necessitating suppression treatments in 2021. Gypsy moth spread from quarantined areas has been limited by an aggressive management program. The USDA National Gypsy Moth Management Program guides gypsy moth management with four strategies: 1) Suppression, 2) Slow-the-Spread, 3) Eradication, and 4) Regulatory activities. Recent eradication treatments have successfully eliminated outlying populations in several eastern, central, and western states. For 20 years, the National Gypsy Moth Slow the Spread Program, comprised of multiple state and federal agencies and a non-profit foundation, has been the focus of gypsy moth management. Slow the Spread annually monitors tens of thousands of traps and treats hundreds of thousands of acres with mating disruption and biological control strategies, which target newly established populations. The program has successfully slowed the rate of spread of gypsy moth with a comprehensive integrated pest management program. Eradication treatments and an international monitoring program have successfully prevented the establishment of Asian gypsy moth in the USA.

Spread, impact and management of hemlock woolly adelgid in eastern North America

Albert Mayfield[a], Scott Salom[b], Robert Jetton[c], Nathan Havill[d], Rusty Rhea[e], and Dave Mausel[f]
[a] USDA Forest Service, Southern Research Station
[b] Virginia Tech, Department of Entomology
[c] North Carolina State University, Camcore, Department of Forestry & Environmental Resources
[d] USDA Forest Service, Northern Research Station
[e] USDA Forest Service, Forest Health and Forest Markets, Southern Region
[f] USDA Forest Service, Forest Health and Forest Markets, Eastern Region

Seven decades after its initial introduction, the hemlock woolly adelgid (HWA) continues to gain new ground in its persistent invasion of hemlock forests in eastern North America. Although eastern hemlock is not a prized commercial timber species, substantial ecological and aesthetic impacts from HWA are compounded by economic costs associated with property value losses, management efforts, and research. Applications of existing tools and new developments in the areas of biological control, chemical control, silviculture, gene conservation, and host resistance are important near- and long-term components of an integrated management approach to this persistent invasive pest.

Keywords: hemlock woolly adelgid, *Adelges tsugae*, biological control, gene conservation, silviculture, integrated pest management

Protection of ash stands against emerald ash borer with biological control: recent progress and potential for success

Jian J. Duan[a], Toby Petrice[b], Nicole Quinn[c], Therese Poland[b], Leah S. Bauer[b], Roy Van Driesche[c], Juli Gould[d], and Joe Elkinton[c]
[a] U.S. Department of Agriculture, Agricultural Research Service, Beneficial Insects Introduction Research Unit, Newark, DE
[b] U.S. Department of Agriculture, Forest Service, Northern Research Station, Lansing, MI
[c] Department of Environmental Conservation, University of Massachusetts, Amherst, MA
[d] U.S. Department of Agriculture, APHIS-PPQ, CPHST Buzzards Bay, MA

Ash trees (*Fraxinus* spp.) are an important component of both natural forests and urban plantings in the United States and Canada. However, the unexpected arrival of emerald ash borer (EAB) [*Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae)] from Asia during the 1990s threatens the persistence of several North American ash species. Despite early efforts by U.S. and Canadian regulatory agencies to eradicate or contain EAB after its discovery in southeast Michigan in 2002, this invasive beetle has spread to 35 U.S. states and five Canadian provinces as of 2021 and has killed hundreds of millions of ash trees in both urban and natural forests. Although systemic insecticides are available to control EAB in ash trees, insecticides are used mainly to protect high-value landscape trees in urban areas. However, in natural forests, biological control using the introduction and establishment of natural enemies from the pest's native range (northeast Asia), provides a potential option for long-term and sustained suppression of EAB. Implementation of biological control for EAB began in 2007 in southern Michigan after APHIS issued permits allowing release of three EAB parasitoid species from

China. These biological control agents included two larval parasitoids, *Tetrastichus planipennisi* (Eulophidae) and *Spathius agrili* (Braconidae), and an egg parasitoid, *Oobius agrili* (Encyrtidae). In 2015, a fourth EAB larval parasitoid, *Spathius galinae* (Braconidae) from the Russian Far East, was also approved for release. With the help of researchers, land managers, and landowners, EAB parasitoids have been released in over 25 EAB-infested states and 2 Canadian provinces since 2007. In this presentation, we first briefly reviewed the current EAB biological control program that involves introduction and establishment of these hymenopteran parasitoids from northeast Asia. Second, we presented our most recent findings on the impact of these parasitoids on EAB population growth and ash stand recovery in the aftermath of the initial EAB outbreak. In particular, we will discuss whether natural enemies (parasitoids) can hold EAB populations to a low enough density to allow ash trees to regenerate and recover.

Status and impacts of laurel wilt disease in North America

John J. Riggins[a], John P. Formby[a,b], Frank H. Koch[c], Jason A. Smith[d], Marc Hughes[d,e], Adam Chupp[f], Natalie Dearing[a], Hannah Bares[a], Natraj Krishnan[a], Richard Brown[a], Kelly Oten[g,h], and Don Duerr[i]

[a] Mississippi State University
[b] Currently, New Mexico State Forestry Division
[c] USDA Forest Service, Southern Research Station
[d] University of Florida
[e] Currently, USDA Forest Service, Institute of Pacific Islands Forestry
[f] University of South Alabama
[g] North Carolina Forest Service
[h] Currently, North Carolina State University
[i] USDA Forest Service, Forest Health Protection

Laurel wilt is a non-native tree disease that continues to impact naïve plants of the family Lauraceae in the United States. This disease is caused by an introduced vector (*Xyleborus glabratus*) and a pathogenic fungal symbiont (*Raffaelea lauricola*). All North American shrub and tree species in the plant family Lauraceae that have been tested thus far are susceptible. We estimated that over 300 million individual redbay trees (*Persea borbonia*), or >1/3 of the pre-invasion population, succumbed to the disease within the first 15 years of the invasion. Genetic markers indicated that the vector and pathogen entered North America as a single introduction. We studied the cold temperature ecophysiology of *X. glabratus* and concluded that less than 1% of sassafras trees in North America occur in a climate cold enough to limit the beetles' eventual range. With apparent minor limitations on the spread of LWD, trophic cascades in the wake of this devastating invasion are possible. To document the radiating impacts of this disease on invertebrates that rely on hosts within the Lauraceae, we compiled a database of all known invertebrate interactions with North American Lauraceae, which yielded a list of 178 associated invertebrate species, at least 24 of which may suffer substantial declines alongside their lauraceous hosts. Overall, the lack of effective control options and a vector system well suited to invading new territory in North America have enabled LWD to become one of the most destructive tree diseases on record.

Successful biological control of winter moth, *Operophtera brumata,* in the northeastern United States

Joseph S. Elkinton[a, b], George H. Boettner[a], Hannah J. Broadley[a, b], Richard Reardon[c], and Ronald Weeks[d]
[a] Department of Environmental Conservation, University of Massachusetts, Amherst, MA
[b] Graduate Program in Organismic and Evolutionary Biology, University of Massachusetts, Amherst, MA
[c] USDA, Forest Service, Morgantown, WV
[d] USDA APHIS PPQ, Science & Technology, Raleigh, NC

Winter moth, *Operophtera brumata* L., native to Europe, invaded the northeastern United States in the late 1990s, where it caused widespread defoliation of forests and shade trees ranging from 2,270 to 36,360 ha per year between 2003 and 2015 in Massachusetts. In 2005, we initiated a biological control effort based on the specialist tachinid parasitoid *Cyzenis albicans,* which had successfully controlled winter moth in Nova Scotia in the 1950s and British Columbia in the 1970s. Each year for 14 years, we collected several thousand individuals of *C. albicans* from British Columbia and released them across widely spaced sites in the northeastern United States. As of 2020, we had established *C. albicans* at 41 of 44 sites from coastal Maine to southeastern Connecticut. By 2016, winter moth densities (pupae/m^2) had declined at least 10-fold at six widely spaced release sites and the decline was coincident with the onset of 10-40% parasitism. At one site where this decline occurred in 2012, winter moth densities have remained low for eight subsequent years. Since 2016, defoliation by winter moth in Massachusetts has been reduced to undetectable levels by aerial survey. DNA sequencing of the CO1 barcoding region of the mitochondrial gene confirmed that all *C. albicans* reared from winter moth were distinct from flies reared from Bruce spanworm, *Operophtera bruceata*, the native congener of winter moth. Parasitism was thus the result of the introduced flies from Vancouver Island and not from native flies. As far as we know, winter moth represents the only example of biological control that has succeeded in reducing a major forest defoliator, attacking many tree species, to non-pest status anywhere in the world.

Impacts of spotted lanternfly on hardwood trees

Kelli Hoover[a], Osaiyekemwen Uyi[a], Emily Lavely[a], and David Eissenstat[a]
[a] Departments of Entomology and Ecosystem Sciences & Management, Penn State University, University Park, PA

Spotted lanternfly (SLF) is a voracious, phloem-feeding planthopper first discovered in North America in one county in Southeastern Pennsylvania about 6 years ago. There are now 32 PA counties in quarantine and breeding SLF populations in 8 other states, most with state-mandated quarantine zones. SLF adults use transportation corridors as a pathway for long distance spread; they hitchhike on railroad cars, trucks, and in cargo holds of airplanes. SLF is polyphagous in both its native and introduced ranges but has a strong preference for the invasive plant *Ailanthus altissima* (tree of heaven). In a study using four established hardwood tree species in large enclosures, half that contained *Ailanthus* and half that did not, SLF

developed from egg to adult and produced viable eggs. However, it took adults two weeks longer to begin oviposition in the absence of *Ailanthus.* This study also allowed us to document host preference by life stage over the course of the season and there was a negative relationship between diameter growth and host preference. In studies using a common garden, red maple, silver maple, and *Ailanthus* had reduced photosynthesis, stomatal conductance, transpiration and carbohydrate content following moderate or high SLF feeding pressure. Documenting impacts on tree health (growth) in forest ecosystems is a difficult undertaking, in large part because of the unpredictable nature of this pest. SLF nymphs and adults can move long distances during a season that lasts from May through early November. Slowing the spread of SLF is proving to be a major challenge for pest managers.

B – Balsam woolly adelgid: range expansion, climate change, and the effects and impacts on ecosystems and management

Lia Spiegel[a] and Iral Ragenovich[b]
[a] USDA Forest Service, Forest Health Protection, LaGrande, OR
[b] USDA Forest Service, Forest Health Protection, Portland, OR

Abstract: In the late 1950's and early 60's balsam woolly adelgid (BWA) caused significant mortality in both the eastern and Pacific northwestern true fir communities. Almost 50-70 years later, it has expanded into the interior west, affecting new ecosystems. Climate change may be an influencing factor in the damage caused. Changes in length of season and warming temperatures may be influencing populations. In some areas where it has been long established, residual host is growing into a new susceptible stage.

This workshop was an open conversation on all aspects related to BWA. Discussions covered a variety of topics including phenology, range expansion, impact on host species, the influence of climate change, the ecological efforts of species loss or conversion, and management options. There were no formal presentations in this workshop; rather it was a conversation about the most current knowledge, observations, and research, as well as recommendations, and identification of research needs.

Summary:

BWA phenology – Early work on BWA phenology was conducted by Balch (1952), Mitchell (1966), Greenbank (1970) and others. Recent work with Greenbank's model suggests that there is only one generation per year. The most recent work in the southeast has focused on Christmas tree plantations at 2600', which represent off-site conditions for Frasier fir. There they are finding 3 generations per year. Some BWA phenology work is just beginning in the intermountain west and Rocky Mountains where BWA has more recently become apparent, and it has been determined there are at least 2 generations per year at elevations over 6000' in Utah. Recent genetic studies indicate that there is no difference between BWA clones in the northwest and the Appalachians.

  - Question – has BWA phenology changed since the earlier works?

- *Range* - BWA has been established throughout the balsam fir host type in the northeast for some time. Surveys in the 1990's determined that it is a chronic pest that survives everywhere in Maine. It has also been in the Adirondacks for many years. It has occupied most of the relict Frasier fir stands in the Appalachians for over 60 years. Large-scale infestation and mortality occurred throughout the Cascades in the Pacific Northwest in the late 1950's and continues to cause mortality there. It has moved slowly and at a less obvious rate through the susceptible species east of the Cascades. More recently, there appears to be range expansion into higher elevations and colder areas of the Rockies with a continental climate. It is now in northern Utah and as far east as central Montana. It appears to be moving northward in western Canada where there is more host. It has been recorded in the coastal grand fir forests of California and is moving north. BWA was introduced into Alaska in urban settings through movement of infested seedlings.

    - Question - what do we know about the environmental effects on BWA since the early works? And are those effects the same in areas where the insect has expanded its range?

- The *dynamics and patterns* of a BWA infestation when it first infests a naïve population of host trees, is that almost all susceptible large host trees are killed within a short period of time. How BWA operates among host species and within stands and sites is highly variable. It is established throughout Maine in balsam fir with most damage occurring in the interior of Maine – the level of damage is dependent on climate – whether maritime, continental, or transitional. Damage is now primarily gouting and crown infestations. In the Adirondacks, they are beginning to see an increase in mortality potentially associated with drought and weather. In both the Appalachians and the Adirondacks, the pattern was to kill large trees, but it did not seem to affect seedlings. In the Appalachians, trees that were seedlings in the 1980's are now becoming infested, so it is believed susceptibility increases at about 35 years of age (Hain); at lower elevations trees are more susceptible where fir is less competitive. In the Adirondacks, trees over about 10' tall are infested. In the west, sites with warmer winters, and moist and marshy sites are more susceptible. Trees of all ages and sizes are equally attacked in central and western Idaho. In areas of northeast WA where BWA infestations are more recent, there is noticeable variability of bole infestations and young stands with gouting.

- *Impacts of BWA feeding* on host. The trees respond to feeding on the stem by producing rotholz – a compression-like wood, but we do not necessarily see a consistent decrease in growth as a result. Studies in the central Appalachians found no decrease in ring width and some increase in ring width with BWA attacks (Liebhold). Gouting can cause a reduction in cone production and so affects regeneration. We don't have a good sense of the population levels required to kill trees. Attacks on trees are highly variable as to whether trees are in the shade. BWA attacks predispose trees to bark beetles and other insects – western balsam bark beetle, fir engraver, etc.
    - Question – what is known about the impacts of BWA on host trees under various conditions and at various stages of the infestation?

- *Ecological effects of BWA* on resources. BWA is removing – although perhaps not extirpating, primary susceptible host species from the ecosystem. In many areas, a primary host will be replaced by other species following an invasion by a non-native species – spruce, hardwoods, etc. However, at high elevations, such as where subalpine fir grows, little is known about ecological effects when there are few replacement species.
    - Question – what are the hydrologic impacts of loss of host?
    - Question – what are the impacts to wildlife in subalpine ecosystems?
    - Question – how does significant mortality influence fire behavior in these ecosystems?

- *Management option*s for BWA include direct control – primarily in high value Christmas tree plantations. Christmas tree plantations management is such that damage does not accumulate. At the beginning of the BWA outbreak on Mt. Mitchell, some trees along the highway were sprayed for scenic value. About 10 years later, those trees still survived.

- Question - How are those trees faring many years later?

Efforts were for active removal of the infested trees in Alaska.

Other management options include cutting down infested trees and conducting restoration efforts. In the NE, the huge patches of mortality do not occur. Management by commercial landowners is to commercially thin stands to remove the fir, as the trees have no future. In the west, in some areas, management is to remove host trees and convert stands to non-susceptible species, but for the most part, management has been passive.

Biocontrol agents from Europe were released in the Pacific Northwest in the 1960's, but subsequent surveys found no population effects, leading to the conclusion that populations in North America are regulated by host condition and weather rather than natural enemies (Mitchell & Buffam 2001). *Leucopus emigrata* was introduced but has not been recovered. Three biocontrol agents have been recovered in BC, OR, WA, ID, MT, CA and AB: *Cecidomyidae thompsoni, Laricobius erichsonii,* and *Leucopus* sp. Little follow-up work has been done since the original introductions. Send bark samples from the Cascades to Nathan Havill to check for predators.

- Question – did the predators accompany BWA in its expansion to the Intermountain west?
- Question - If predators and parasites occur, they do not appear to influence BWA population levels where it has been established for many years. How much impact on the BWA populations do biocontrol agents have? (none from initial studies).

Host tree susceptibility/resistance – There is variability among the host fir species in terms of susceptibility. Some species such as noble fir are most resistant; others such as grand fir are intermediate; subalpine fir and Frasier fir are highly susceptible. Subalpine fir is the most susceptible in the intermountain west, but grand fir is also attacked in some locations. In NE Oregon, damage is limited to subalpine fir. In central and western Idaho, both species are equally attacked. In NE Washington, grand fir can be heavily damaged when growing in mixed stands with subalpine fir; when not intermixed, damage to grand fir is usually minor gouting. Recently, there has been increased interested in resistance of the most susceptible host species – Frasier fir and subalpine fir. Work at UNC has been examining resistance of Frasier fir – studies indicate there is variability in resistance between clones of trees primarily regarding gouting. Other studies in the west are beginning to evaluate seed lots for resistance within tree species.

- Question – Is there resistance in the most susceptible species?
- Question – how much resistance is environmental and how much is genomic?

Conclusions:

Many topics were only briefly discussed including BWA phenology, current research, fate of susceptible species, and potential management needs.

1. There are still many unknowns about the phenology of BWA, especially in areas where it has recently become established.

2. How BWA expresses itself and its impacts on various host species is highly variable and varies considerably in terms of age of outbreak, site conditions (density, elevation, moisture, inland vs maritime, etc.), host (species, size, etc.), and climate. May need to focus efforts on the most susceptible species.
3. Is there genetic resistance in highly susceptible species? Is there an effective short-term way to determine genetic resistance?
4. Little work has been done with biological control agents in North America since the 1960’s. However, tree killing continues where predators were successfully established.
5. Little is known about the ecological effects of removal of host species, especially from ecosystems with limited replacement options.
6. What are the potential effects of projected climate change on susceptible species? How will that determine the future and our ability to manage the species in the future.
7. Participants desire to continue conversations about specific topics when there is more time to dive into individual topics.

Keywords: balsam woolly adelgid; phenology, climate change, ecosystem impacts, management

Acknowledgements: Participants included entomologists, geneticists, and silviculturists and represented many agencies including the US Forest Service, Canadian Forest Service, BC Ministry of Forests, Maine Forest Service, University of Idaho, Utah State University, North Carolina State University, and Cary Institute. The following people participated in the workshop and contributed significantly to the discussion: Wayne Beck, Gwylim Blackburn, Celia Boone, Christopher Clark, Ryan Davis, Gina Davis, Darci Dickinson, Nicole Green, Fred Hain, Nathan Havill, Don Heppner, Jeff Hicke, Mike Johnson, Grayson Jordan, Allison Kanoti, Scott Kolpak, Sandy Liebhold, Gary Lovett, Laura Lowrey, Dan Ott, Iral Ragenovich, Liz Rideout, Karen Ripley, Ben Smith, Richard Sniezko, Cyndi Snyder, Lia Spiegel, and Beth Willhite.

C – Biochar as a soil amendment treatment for restoring forest stands

Moderator: Stephen Cook[a]
[a] University of Idaho, Department of Entomology, Plant Pathology and Nematology

As a soil amendment, biochar is useful for sequestering carbon, with other benefits related to its physical structure that increases the retention of H_2O and water-soluble nutrients while reducing soil acidity and nutrient leaching. Biochar treatments can directly impact plant health and may improve habitat for beneficial microorganisms. However, application of biochar can also result in shifts in soil microbial communities. Some insects show delayed development, decreased fecundity, lowered egg hatch and increased mortality when exposed to biochar under various application conditions. Such effects require further examination. The session was set up to introduce participants to the uses of biochar in forest systems as well as the potential impacts (both direct and indirect) on soil properties and the biological communities that occur in the application area.

Impact of biochar on soil physical, chemical, and biological properties

Deborah S. Page-Dumroese[a] and Joanne M. Tirocke[a]
[a] USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Lab, Moscow, ID

Abstract

Restoring or enhancing soil properties on forest, range, mine, or agricultural soils is becoming increasingly important. In particular, threats to soil from drought, intense rain, flooding, heat, and wildfire can reduce the productive capacity of the soil and also reduce our ability to grow food and fiber or regulate carbon (C), water, or nutrients (Blanco-Canqui 2021). Creating wood-based biochars from material normally burned in slash piles is an opportunity to increase forest health by decreasing wildfire risk or insect and disease outbreaks (Rodriguez-Franco and Page-Dumroese 2021). Forest restoration efforts to reduce stand stocking is common on public lands, but there is often no end use for limbs, branches, cull sections, or unmerchantable round wood (Anderson et al. 2016). However, biochar made from this 'waste' wood is one way to increase woody residue values while also improving forest stand conditions (Bergman et al. 2016), improving soil conditions, and mitigating climate change. Biochar is a high C (25-95% C) substrate and its addition to soil can rapidly increase soil C levels (Blanco-Canqui et al. 2020; Liu et al. 2016) depending on soil type, biochar feedstock, application rates, and conditions under which biochar is created. Further, creation of biochar using mobile pyrolysis units, kilns, or carefully built slash piles (Page-Dumroese et al. 2017) at log landings or on skid trails reduces transportation costs while creating biochar on-site.

Soil Changes

Physical properties: Biochar is highly porous and therefore using it on organic matter-degraded soil or those that are compacted has many advantages. It can improve soil porosity, pore-size distribution, bulk density, moisture holding capacity, infiltration, and hydraulic conductivity (Atkinson et al. 2010; van Zwieten et al. 2012). It is important to note that different soil taxonomic classes will respond differently to char additions (Table 1). This change in water relations, however, could be extremely helpful for restoring log landings and skid trails within harvest units. Adding biochar can also help form soil micro-aggregates (Verheijen et al. 2009) and increase vegetation establishment (Adams et al. 2013). Biochar can prevent the surface soil from sealing and thereby reduce sedimentation and runoff (Luce 1997). By changing soil physical properties, biochar may also increase forest health. For example, amending silt loam soils with 10% biochar made from lignocellulose increased plant water use efficiency of pine-oak forest understory plants (Licht and Smith 2018). One important change in soil physical properties associated with biochar addition is the increased potential for storing water. The addition of 1% organic matter or biochar can increase water storage in the soil by 1-3% (Libhova et al. 2018) and this can be particularly important on coarse-textured soils (Basso et al. 2013).

Table 1. Soil moisture content changes associated with biochar additions in two soil taxonomic classes (after Page-Dumroese et al. 2016. Chapter 15).

Taxonomic Order	Biochar Addition ---- $v\ v^{-1}$ ----	Soil Moisture ---- $w\ w^{-1}$ ----
Andisol	0	0.38
	12	0.40
	25	0.43
	50	0.47
Mollisol	0	0.18
	12	0.21
	25	0.25
	50	0.28

Importantly, biochar can increase plant available water by 38% in coarse-textured soil, 19% in medium-textured soil, and 16% in fine-textured soils (Blanco-Canqui 2017, Edeh et al. 2020, Razzaghi et al. 2021) and highlights the importance of using biochar on coarser-textured soils. Understanding how much plant available water that results from biochar applications should be assessed for each soil and biochar type (Atkinson 2018).

Chemical properties: Soil chemical changes associated with biochar additions are dependent on the type, quality, and quantity of biochar applied. Most biochars tend to be alkaline (pH >6.0) and can act as a liming agent in acidic soils (Glaser et al. 2002, Xu et al. 2014). It has also been shown to increase cation exchange capacity and, because of the increase in exchange sites, it can reduce nutrient leaching through the soil profile (Ducey et al. 2013). As the biochar ages within the soil these properties may change and are dependent on soil, climatic regime, biochar feedstock, and pyrolysis conditions.

Biological properties: Biochar is incredibly porous and therefore provides great habitat for soil microbial communities. It can also stimulate both nitrification and denitrification processes and reduce N_2O emissions (Xu et al. 2014). Soil microbial community composition and function may also change in forest soils as a result of biochar additions. Early work noted that biochar is particularly beneficial for fungi (Warnock et al. 2007), but more recent work has also shown that bacterial populations and an the bacterial:fungi ratio may also be increased (Gomez et al. 2014).

Biochar and Forest Health: Increasing soil health by using biochar can also improve forest health by making vegetation more resilient to drought and a changing climate. Increased soil health can also mean that trees are less susceptible to insect or disease attack or better able to withstand infestations because of a change in soil water holding capacity and available water. In addition, because of the changes in C, nutrients, and microbial communities, biochar has been shown to reduce disease severity of several different pathogens. Although most of the work has been done on agricultural crops (e.g., Elad et al. 2010, Elmer and Pignatello 2011) the defense-enhancing mechanisms of biochar may also be important for forest vegetation since these sites are often low in organic matter and nutrients and biochar can improve nutrient retention and water holding-capacity.

Biochar is a rapid method for increasing soil C and it also imparts other benefits such as increase water holding, reduced leaching, or altering soil microbial communities. In addition, on many degraded sites (e.g. skid trails, log landings) biochar can increase soil cover; thereby reducing the potential for wind and water erosion. The key to successful deployment of biochar, however, is to understand the type of biochar, soil, and climatic regime. Usually, degraded soils have a greater response than soils with a high organic matter content, but many soils benefit from biochar additions and the ecosystem benefits can be even greater (Blanco-Canqui 2021).

Keywords: soil health, forest health, forest restoration

Acknowledgements: The authors wish to acknowledge the contributions of the numerous University, Forest Service, and industry partners that make biochar research possible.

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Effects of biochar addition on fungal communities: Implications for forest insects

Kymberly R. Draeger[a], Daniel L. Lindner[a*], Michelle A. Jusino[a], Deborah S. Page-Dumroese[b], Jonathan M. Palmer[a], Mark T. Banik[a]

[a] USDA Forest Service, Northern Research Station, Center for Forest Mycology Research, Madison, WI

[b] USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Lab, Moscow, ID

* Presenter

Abstract

Many western forests are severely overstocked, creating a critical need to understand how forests can be thinned while maintaining biodiversity and other ecosystem services, such as carbon sequestration. Wood-inhabiting fungi play a critical role in carbon cycling and carbon

sequestration. However, the effects of different management techniques on wood-inhabiting fungal communities have rarely been investigated. Here, we implemented a manipulative experimental design to determine the effects of thinning on fungal communities, with four levels of slash retention as well as four combinations of compensatory soil amendments (non-amended control, biochar, fertilizer, or fertilizer+biochar). We sampled our treatment plots for three years using above- and below-ground wood stakes (pine and aspen) and also conducted annual surveys of woody material for fungal fruiting bodies. Fruiting bodies were identified using a combination of morphology and DNA sequencing, while high-throughput DNA sequencing was used to identify fungi that colonized the wood stakes. Although differences in diversity and richness of fruiting bodies were not observed across treatments, the different levels of slash retention did affect the community composition of wood-inhabiting fungi observed as fruiting bodies. In contrast, the DNA-based survey of wood-colonizing fungi indicated that fungal communities were sensitive to levels of slash retention as well as different soil amendments, including biochar addition. Future work will determine how these changes in the fungal community may affect decomposition rates and explore how changes in the fungal community may affect other organismal groups, such as the many forest insects that interact with fungi.

Research goals and study design

Our research goals were to contribute to the understanding of how wood-inhabiting fungal communities respond to different forest management practices in western North America, while specifically investigating how richness, diversity and community composition of fungi may change in relation to different levels of slash retention and to the addition of different combinations of soil amendments (fertilizer and biochar) (Draeger 2018). Two sites were installed on the University of Idaho Experimental Forest in 2013 with the sites being separated by approximately 1 km. Sixteen 400 m^2 study plots were established at each site with biomass treatments at four levels (no thinning control, no slash removed, slash left on site, or 2x the amount of slash left on site) and four types of soil amendments (non-amended control, biochar, fertilizer, or fertilizer+biochar). Biochar was from Evergreen Forest Products (Tamarack, ID, USA) and was produced from mixed-conifer mill residue at 890ºC (Sherman et al. 2017) and applied hydraulically to each plot at a rate of ~2.5 $Mg\ ha^{-1}$. This created 16 different treatment combinations (4 slash retention levels by four types of soil amendment) replicated across two sites.

Surveys of wood-inhabiting fungal fruiting bodies

Fungal fruiting body sampling methods follow established protocols (Mueller et al. 2004). The following characteristics were reported when a fruiting body was encountered: preliminary fungal species identification, substrate type (branch, log, suspended log, snag, stump, and living tree), wood substrate species, diameter class, and decay class following the five-class system of Maser et al. (1979). Fruiting bodies were inventoried unless their state of degradation precluded identification.

Over 3 years of survey, 1,002 wood-inhabiting fungal fruiting bodies were collected and identified using morphology and DNA-sequencing. One hundred and twenty-nine species were identified in total, all of which were in the phylum Basidiomycota. Many species (22 of the 129 species, or ~17%) did not match known species descriptions, and species accumulation curves indicate that more species would be found with more extensive sampling. No significant differences were observed among treatments for species richness or diversity. However, fungal community composition was influenced by biomass retention, with the level of slash retention significantly influencing the fungal community composition in the first and third years of sampling ($p < 0.04$). Soil amendments generally did not affect the fungal community, although there was a moderate influence on the fungal community composition in the second year of sampling (2015, $p = 0.064$), with fertilization being the primary driver of differences ($p < 0.02$). Biochar amended plots did have the greatest species richness of fruiting bodies, although the difference was not statistically significant.

Surveys of wood-inhabiting fungi using high-throughput DNA sequencing

Using protocols described by Jurgensen et al. (2006), 25 loblolly pine (*Pinus taeda*) and 25 aspen (*Populus tremuloides*) stakes (2.5 x 2.5 x 30 cm) were inserted vertically to a depth of 30 cm in the mineral soil of all treatment plots. An additional 25 pine and 25 aspen stakes (2.5 x 2.5 x 15 cm) were affixed on top of the surface organic horizons. Installation occurred in spring of 2014. Sampling occurred each year for three years, and during sampling, five aspen and five pine stakes were removed from both the mineral soil and litter layer location of each plot and wood shavings were extracted from each stake using DNA-sterile methods.

Fungi inhabiting the wood stakes were identified using high-throughput amplicon sequencing (HTS). Samples for DNA sequencing were collected using methods similar to those described by Lindner et al. (2011). HTS was performed on the fungal ITS2 fragment using an Ion Torrent PGM and bioinformatic analyses were performed using AMPtk (Palmer et al. 2018). A single-copy positive community control (SynMock) was used to parameterize the bioinformatic pipeline. We used multivariate hypothesis tests to compare differences in fungal community composition across treatments and sampling methods.

After three years of sampling, over 2,000 operational taxonomic units (OTUs) were identified. Approximately 50% of identified taxa were assigned to the phylum Ascomycota and 33% to Basisidiomycota. Species of stake and location (surface or within the mineral layer) were highly significant in influencing both fungal richness and fungal community composition ($p < 0.01$). Biomass treatments significantly influenced the fungal communities present within surface stakes every year of data collection ($p < 0.05$), whereas for the stakes in the mineral soil, biomass treatment was only significant in the second year ($p < 0.05$). Initially the 2X biomass treatment had fewer OTUs, although by the third year the 2X biomass treatment had the greatest OTU richness. Fungal community compositions was also significantly influenced by soil amendments. Fungal colonization of both aspen and pine surface stakes was influenced by soil amendments in the first year ($p < 0.01$), whereas only surface aspen and mineral pine stakes were influenced by soil amendments in the second year ($p < 0.05$). By the third year, both pine and aspen surface stakes had significant differences in fungal community composition due to soil amendments ($p < 0.05$).

Comparison of methods

The two sampling methods revealed significantly different fungal communities. Fruiting body surveys sampled a range of substrates and identified Basidiomycota species, including multiple important forest pathogens. DNA-based methods produced more data, identified more OTUs ($p < 0.001$) and were more sensitive to biomass removal and soil amendment treatments. Both methods have advantages and disadvantages, and success with each method depends on the questions being asked and the resources available.

Conclusions and future directions

Biomass harvesting and soil amendments have the potential to alter fungal communities in conifer-dominated forests of western North America and this has implications for forest health and productivity. Changes in the fungal community may affect multiple ecosystem services, such as humus formation and carbon sequestration. In addition, the changes in the fungal community may have cascading effects on other organismal groups that interact with fungi, especially for insect groups that interact closely with decomposing wood, such as beetles and termites. More research is needed to understand the interactions among forest management techniques, wood-decomposing fungal communities, and wood-associated insect groups.

Keywords: biochar, decay, decomposition, wood-decay fungi

Acknowledgements: The authors wish to acknowledge the contributions of Mark Coleman (Professor, University of Idaho), Glen Stanosz (Professor Emeritus, UW Madison), Karen Nakasone (USDA Forest Service, Northern Research Station), Joanne Tiroke (USDA Forest Service, Rocky Mountain Research Station), and Wei Wei Wang (Beijing Forestry University) for their contributions to this project.

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Biochar influence on subterranean termites: 36-month evaluation

Brad M. Kard[a], Deborah S. Page-Dumroese[b], Martin F. Jurgensen[c], Joanne M. Tirocke[b], Stephen P. Cook[d], Martin MacKenzie[e], and Kevin T. Shelton[a]

[a] Dept. of Entomology and Plant Pathology, Oklahoma State University, Stillwater, OK

[b] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Moscow, ID

[c] College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, MI

[d] Dept. of Entomology, Plant Pathology and Nematology, 606 Rayburn Street, MS 2329, University of Idaho, Mosco, ID

[e] U.S. Department of Agriculture, Forest Service, Stanislaus National Forest, Sonora, CA

Abstract

This first interim research report concerning subterranean termite activity summarizes the 36-month evaluation of a 5-year study-in-progress on the Stanislaus National Forest, Calaveras County, California, within the Sierra Nevada Mountains. The Lakemont timber salvage site was clear-cut during 2017 and received biochar treatments during November 2017. Wood stakes, ground-boards and PVC termite monitoring stations were installed during 2018. Evaluation and sampling began during 2019. Study plots were established across the open field salvage site. Non-disturbed forest tree plots were also established on the open field periphery. Open field and tree plots were randomly assigned one of two biochar amendments to the soil surface or designated as a non-treated control. Wood stakes were placed in plots to monitor decay and changes in wood soundness each year as well as evaluate subterranean termite activity. To gain additional insight into subterranean termite activity, all open field and tree plots also contain in-ground termite monitoring stations and soil-surface ground-boards. Currently, forest tree plots have not exhibited sufficient termite activity to draw conclusions concerning effects of biochar on foraging termites. However, biochar applications to open field soil may have increased termite activity in the high rate open field plots. The highest biochar application rate of 22,417 kg•ha^{-1} (10 tons•acre^{-1}) exhibited the greatest termite foraging activity after 36 months compared with the 6,725 kg•ha^{-1} (3 tons•acre^{-1}) and non-treated control plots. However, another two years or longer evaluations should more clearly identify definitive trends and allow more accurate conclusions concerning effects of biochar soil amendments on subterranean termite foraging activity.

Overview

For the termite part of this biochar amendment field research project, activity of subterranean termites within the open field and tree plots continues to be evaluated. The open field salvage area soil is extensively disturbed, scarified and rutted, and several areas are severely compacted due to heavy equipment operating on wet soil. In addition, within two years after the salvage operation ground-cover was nearly 100%, dominated by the low-growing plant 'mountain misery' (*Chamaebatia foliolosa* Benth., aka bearclover). Widespread amounts of coarse woody debris remain throughout the open field site. Because subterranean termites are beneficial within the natural soil environment and are primary reducer-decomposers of dead wood (Krishna and Weesner 1969, Thorne 1998), evaluating effects of biochar on their repopulating and foraging activities on disturbed salvage sites as well as their activity within non-salvage adjacent tree sites is of interest. This research will provide insight into overall subterranean termite activity within biochar amended and non-amended soil in both natural forest sites and disturbed open field salvage sites.

The Lakemont timber salvage site is located near the town of Arnold, California, on the Sierra Nevada Mountains central western slope. The site encompasses approximately 8 ha (20 acres) with a southeast aspect and 13% slope north-to-south. Site elevation ranges from 1,210- to 1,262-m (3,970 to 4,140 feet) AMSL (38°14.874'N–120°22.697'W). The terrain is rough and littered with limbs and stumps due to logging activities. A severe drought for the past two years has resulted in a hot, dry open field soil surface during summer months.

Objectives

Several factors concerning subterranean termites are being evaluated through at least five years. These factors include:

- Relative frequency of termites within the different biochar treatments – tree plots and open field plots.
- Percent attack by termites on 'surface' and 'mineral soil' wood stakes.
- Percent attack by termites on surface ground-boards, and wood inside PVC monitoring stations.
- Determination of ASTM damage ratings for all stakes, ground-boards, and monitoring station wood.
- Comparison of mass loss from pine and aspen stakes due to termite feeding within and between tree plots and open field plots.
- Comparison of mass loss from ground-boards, and wood billets in PVC monitoring stations, within and between tree plots and open field plots.
- Estimation of relative numbers of termites feeding on stakes, ground-boards, and monitoring wood.
- Identification of different subterranean termite species and colonies.

Materials and Methods

Three tree study blocks of non-disturbed forest consisting of three mature trees per block are currently established on natural, non-salvage wooded areas immediately adjacent to the open field salvage site. Each tree per block was randomly assigned one of two biochar treatments or designated as a non-treated control. In addition, three study blocks, each consisting of three 0.4 ha (1 acre) plots are established on the approximately 8 ha (20 acre) Lakemont open field salvage site. One of the two biochar treatments to the soil surface or the non-treated control was randomly assigned to one of the three plots per block for both tree and open field plots. Treatments: No biochar application to the soil surface (control plot); biochar low rate – 6,725 kg•ha^{-1} (3 tons•acre^{-1}); biochar high rate – 22,417 kg•ha^{-1} (10 tons•acre^{-1}).

Within each of the nine non-disturbed single tree plots, four 10.2-cm diameter x 20.3-cm tall (4-inch diameter x 8-inch tall) PVC in-ground monitoring stations that contain pine billets were vertically inserted into the soil approximately 1 m (3 feet) from each tree and spaced 90° apart. Two of these stations have open bottoms to allow entrance by foraging termites. Bottom openings of the other two stations are enclosed with stainless steel mesh to exclude subterranean termites and other soil-dwelling animals. In addition, four 15- x 30- x 2.5-cm (6 x 12 x 1 inch) pine ground-board (GB) monitors were placed on bare mineral soil and equi-spaced around each tree adjacent to the PVC monitoring stations. Two ground-boards are open (non-enclosed) and two ground-boards are completely enclosed in stainless steel mesh (Figure 1). For open field plots, in-ground PVC monitors and surface ground-boards along with two larger, wood-filled centrally located monitoring stations were installed and remain in each of these nine plots. Enclosed monitors and ground-boards allow for wood mass loss comparisons with and without termite feeding activity (Figure 2).

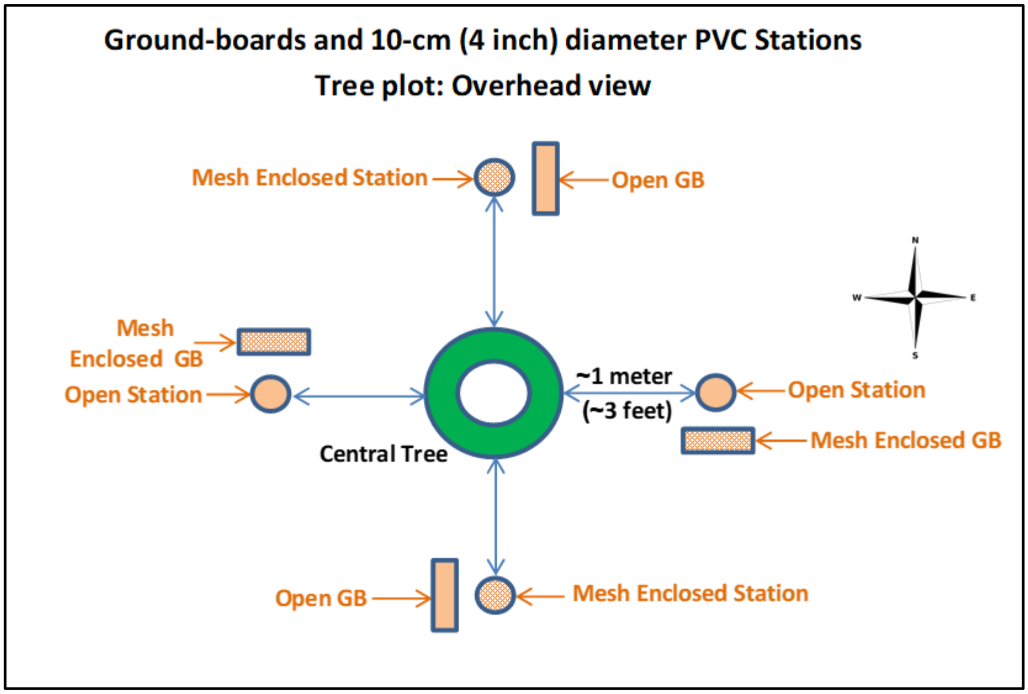
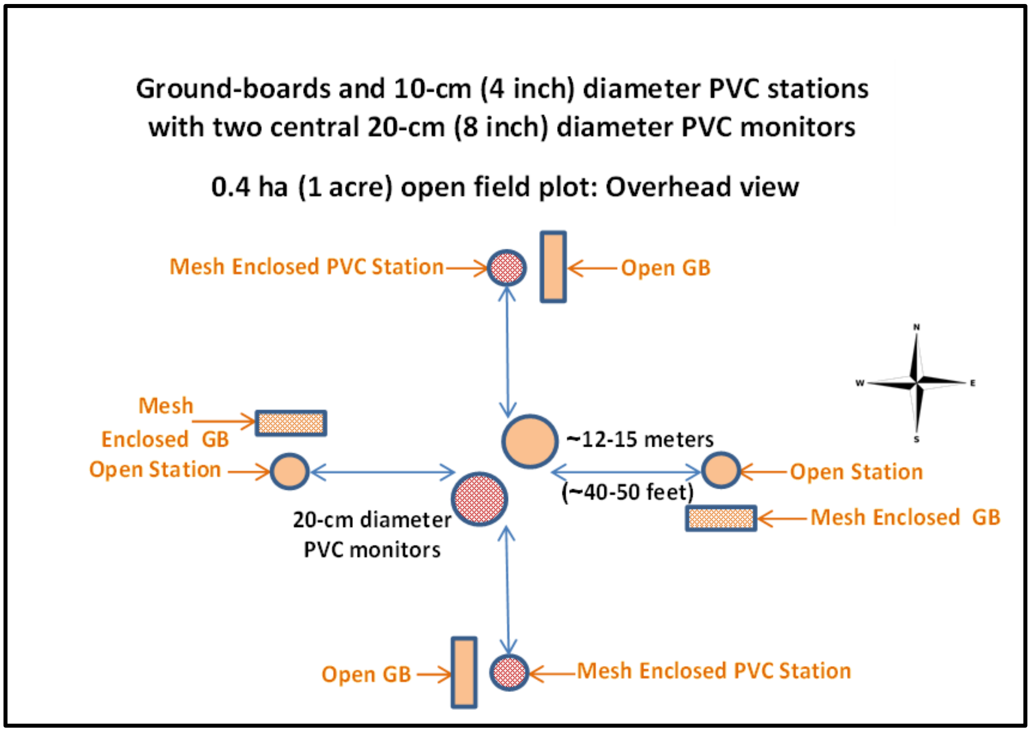


Figure 1. Tree plot monitoring station and ground-board (GB) configuration.



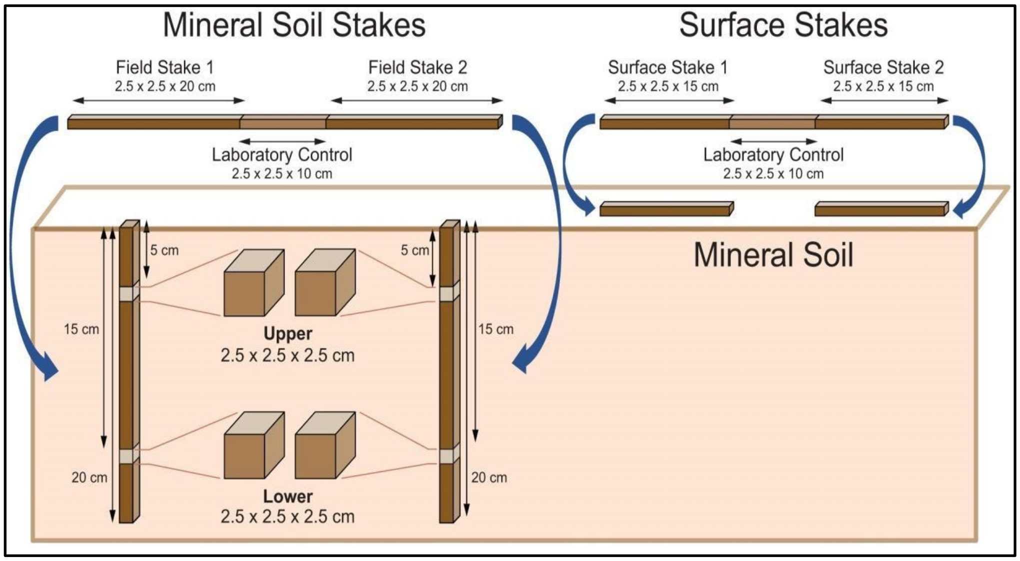


Figure 3. USDA Forest Service and Michigan Technological University vertical Mineral Soil Stakes and Surface Stakes configuration (used by permission–Jurgensen et al. 2020).

In addition to the PVC monitors and ground-boards, two sets of stakes consisting of five aspen plus five southern yellow pine stakes per set were emplaced in the nine open field plots. These sets of 10 stakes each are referred to as "surface stakes" because they are placed on the bare mineral soil surface. The second identical set of 10 stakes is vertically inserted into the soil and referred to as "mineral soil stakes" (Figure 3). These two sets of ten stakes each were replicated five times in each open field plot. Two sets per plot (one set each of 10 surface stakes and 10 mineral soil stakes) are removed and evaluated for decay and changes in wood soundness plus termite damage each year. For tree plots, the same arrangement of two sets of 10 stakes each (five aspen plus five pine stakes per set) were placed in one low biochar, one high biochar, and one control tree plot with all stake sets replicated five times (Page-Dumroese and Tirocke 2021).

Interim findings and discussion (36-months post-biochar applications)

To evaluate subterranean termite activity, all field and tree plot surface and mineral stakes, ground-boards, and PVC monitoring station wood billets were evaluated for termite activity and rated for termite damage using the ASTM rating scale (ASTM 1999). Currently, single tree plots have not shown sufficient termite activity to draw definitive conclusions. However, in the open field salvage plots, the plots with the high biochar application rate exhibited greater termite activity and feeding damage to mineral soil stakes compared with the low rate and control plots (Figure 4). To date, surface stakes have not been contacted by termites. This is possibly due to the hot, dry soil surface during a continuing long-lasting drought over the past two years. Over the next two years, clearer termite activity trends may emerge. Therefore, at this time it is somewhat early in the study to identify and validate definitive trends or draw accurate long-term conclusions concerning overall termite activity within the open field plots although the high biochar plots currently show the greatest termite activity.

Termites fed on a total of 10 pine and 12 aspen mineral soil stakes across all field plots, currently showing no definitive feeding preference for either wood. In the high biochar plots termites damaged a total of 17 mineral soil stakes, compared with four soil mineral stakes in the low biochar plots and one mineral soil stake in control plots. However, only two pine mineral soil stakes contained active termites, plot 1 (high rate; ASTM 7) and plot 8 (control; ASTM 9) (Figure 4).

The large 20-cm (8 inch) diameter central PVC monitors in the open field plots have yet to be located by subterranean termites. These monitors should eventually collect termites for taxonomic identification and delineation of termite activity and foraging distances within the field plots. Presence of different termite colonies within a plot can be determined by genetically comparing specimens from stakes, ground-boards and PVC monitors, providing insight into species diversity and colony density. Wood in the large monitors was pre-weighed for comparison of wood mass loss between open and mesh-enclosed configurations

Many downed logs in natural areas surrounding the salvage site are populated with carpenter ants and dampwood termites as well as subterranean termites. These logs are a source of subterranean termite dispersal flights into open field plots. Numerous stumps and woody debris on the salvage site will serve as nesting and food resources. The study is three years old. This is a short period for termites to re-populate such a severely disturbed field site. Evaluations during the next two years will increase our knowledge of effects of biochar applications to soil on termite foraging and feeding behavior and evaluate if biochar amendments are beneficial or detrimental to termite activity.

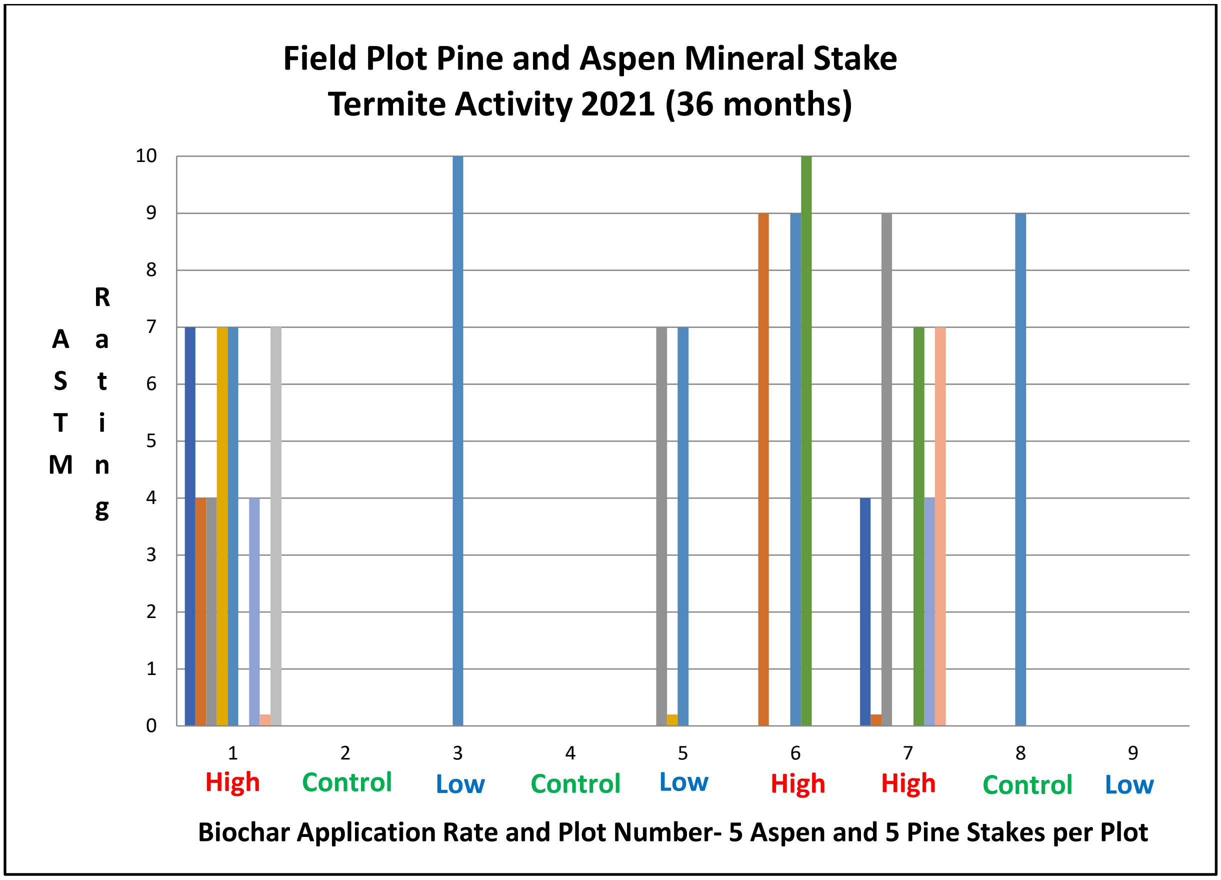


Figure 4. ASTM damage ratings to mineral aspen and mineral pine stakes by plot and biochar application. Five aspen stakes and five pine stakes per open field plot.

Keywords: biochar, carbon soil amendment, subterranean termites, timber salvage restoration

Acknowledgments: We thank Curtis D. Kvamme, USDA Forest Service, Stanislaus National Forest, California, for help during field evaluations.

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Changes in insect communities following biochar applications in restoration projects

Stephen Cook[a], Stacey Rice-Marshall[a], and Toriani Kent[a]
[a] University of Idaho, Department of Entomology, Plant Pathology and Nematology
Moscow, ID

Rationale

Biochar can be used in forest restoration activity as a soil amendment. Among the potential benefits provided by biochar are carbon sequestration, increased retention of H_2O and H_2O-soluble nutrients while simultaneously reducing soil acidity and nutrient leaching. Biochar treatments can directly impact plant health and improve habitat for beneficial microorganism but can also cause shifts in soil microbial communities. While biochar has been demonstrated to impact multiple insect species (e.g. Salem et al. 2013; Marks et al. 2014; Hou et al. 2015), there is no overall evaluation on the impacts of biochar to communities of forest insects. The overall goal of our work is to develop a better understanding of the potential impacts of applied biochar on populations (and communities) of forest insects. The work is being pursued through a combination of laboratory experiments in which insects are exposed to biochar under controlled conditions and field trials that examine insect response to exposure under more natural conditions.

Initial lab exposures

We exposed multiple species of forest insects including *Formica obscuipes*, *Ips pini*, *Temnochila chlorodia* and *Enoclerus sphegeus* to dry biochar in confined arenas. When the insects were in physical contact with the biochar, exposure increased mortality for all of the tested species except *Enoclerus sphegeus* and particle size did not affect mortality (Cook and Rodriguies de Andrade Neto 2018). However, even when applied dry, biochar does not remain dry under field conditions. Therefore, we exposed two weevils (*Larinus minutus* and *Cyphocleonus achates*) to a combination of biochar and soil. The weevils are introduced biocontrol agents that feed on spotted knapweed, so to be useful in an integrated management program against the weed, biochar would not be useful if it decreased survival or feeding ability of the insects. We found no significant increase in mortality based upon biochar presence for these exposures.

Continuing along these lines of experimentation, we reared Douglas-fir tussock moth larvae on synthetic diet in the laboratory. Two sets of experiments compared larval survival and weight gain on diet with no biochar treatment versus on diet that had been surface-treated with biochar or had biochar incorporated throughout the diet. In these experiments, larvae that fed on diet with biochar showed significant decreases in both survival and weight gain at the highest amounts tested.

In future laboratory experiments, we will examine the potential impacts of exposure to biochar on other feeding guilds (natural enemies such as parasitoids) and determine its effects on insect digestive systems (does the material impact nutrient absorption).

Small plot field trials

Biochar is typically applied as a broadcast, surface treatment in the field when used following multiple disturbance events such as harvesting. To investigate the impact of these types of applications on communities of insects involved with decomposing, we applied biochar to ponderosa pine bolts in a pair of experiments. In both experiments, we felled small ponderosa pines, and cut them into 1 M bolt sections. We used the bottom bolt sections and randomly assigned one as the control and applied biochar to the surface of the second bolt. In one experiment, we placed ipsdienol on each bolt to induce attack by the resident *Ips* population. We did not use any lures in the second experiment.

When ipsdienol was placed on the bolts, there was no difference in the attack density (based upon nuptial chambers) or brood production (based upon adult emergence) of *Ips pini* between control and treated bolts. There were cerambycid and buprestid larvae present in the phloem when the bark was peeled. However, we removed the bark prior to them completing development so that the evidence of nuptial chambers would not be destroyed by their foraging.

No lures were included in the second experiment so that we could examine the potential impact of biochar on the utilization of pine bolts by the insect community. After exposure in the field, bolts were brought into the lab and maintained. Emerging insects were collected and identified and included several species of scolytids, buprestids and cerambycids as well as other families. Initial analysis indicates a significantly higher measure of species richness for the communities emerging from control bolts versus the treated bolts.

The third small plot study we conducted was also to determine if the presence of biochar would impact the community of surface insects captured in pitfall traps throughout the year. We treated the ground around covered pitfall traps and collected monthly for over a year. We are currently identifying the captured insects and analyzing the data for species richness and diversity.

Larger plot field trials

Our final efforts to date have been to apply biochar onto larger plots and monitor the overall insect community for multiple years following the applications. On the first set of plots, we combined treatments of biomass reduction with or without soil amendments (biochar or fertilization). We collected prior to treatments, directly following treatment application and during the following two years. We used Lindgren funnel traps, panel traps (one blue and one yellow) and pitfall traps to monitor the insect communities. None of the traps had any lures. We are still identifying specimens and analyzing the data. Initial analysis indicated a significant impact on generic richness of the ant community on the sites, with the least change from pre-treatment measures occurring in biochar-treated plots. Identification and analysis of other community members is ongoing, with an emphasis on various families (or sub-families) of beetles including Carabidae, Cerambycidae, Buprestidae and Scolytinae).

We are also continuing to examine and analyze data from a project in the Stanislaus National Forest. A western pine beetle infestation in a primarily ponderosa and sugar pine stand was salvage-logged and biochar applications were made in the logged area as well as in adjacent, non-damaged forest. We are again using multiple types of traps and have just begun sorting and identifying this year's captures.

Conclusions and future directions

We are still early in the evaluation process of how biochar applications may impact insect populations and communities in forest systems. However, laboratory trials demonstrated that exposure to dry biochar resulted in significantly increased mortality in three of the four insect species tested. This increased mortality was not observed when insects were exposed to biochar under more natural conditions. Decreased species richness was found for insects emerging from bolts of ponderosa pine that were surface-treated with biochar and there was an increase in mortality of Douglas-fir tussock moth caterpillars when they were exposed to biochar on the surface of, or incorporated into, synthetic diet. We are examining the impact of biochar on other feeding guilds of insects when it is applied to plant surfaces. We are also continuing to examine the impact of biochar applications on plant resistance parameters (in both trees and forbs) and insect community structure.

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D – Open Session 4

Moderator: Jeff Garnas[a]
[a] University of New Hampshire

Topics varied in this open session. Of the six talks, two focused on the control of an invasive species, though both the targets and the approach to control diverged dramatically. James Vogt and colleagues presented on the potential suppression of an invasive tree species, the Chinese tallow tree (*Triadica sebifera*), using classical biological control. Chinese tallow tree is perceived as valuable by some beekeepers, however, complicating public perceptions of potential biocontrol of this species. Flavia Pampolini presented an excellent talk on the potential for gene silencing approaches to control emerald ash borer. Assays using double-stranded RNA molecules showed good efficacy and high specificity as a control measure, paving the way for the development of an RNAi system. However, significant hurdles concerning field delivery must still be overcome. Kevin Chase presented on data from a large-scale field study of the bark beetles *Hylurges ligniperda* and *Ips pini* in New Zealand where both insects are currently invading. Chase and colleagues provide evidence for the existence of an Allee threshold for establishment in these species, though the role of propagule number in determining establishment success was stronger in *H. ligniperda*. Sullivan et al. discussed the chemical ecology of *Ips calligraphus* in the southeastern United States and shared findings concerning to detection of aminitol as a component of the insect's pheromone blend. The last two talks of the session and of the conference focused on biodiversity. Ulyshen et al. explored the role of prescribed fire on pollinator diversity in the longleaf pine ecosystem finding a positive effect of burn heterogeneity ("pyrodiversity") on both bees and butterflies, but an overall negative effect of high burn frequency. Finally, Clayton et al. discussed relationships between downed woody debris and other habitat factors on longhorn beetle and bee diversity in a forest in Georgia.

What's the buzz? Bees, biological control, and Chinese tallowtree (*Triadica sebifera*)

James T. Vogt[a], Rabiu Olatinwo[b], Michael D. Ulyshen[a], Rima D. Lucardi[a], and Jessica L. McKenney[c]
[a] USDA Forest Service Southern Research Station, 320 E. Green St., Athens, GA
[b] USDA Forest Service Southern Research Station, Alexandria Forestry Center, Pineville, LA
[c] Department of Entomology, Louisiana State University, Agricultural Center, Baton Rouge, LA

Chinese tallowtree [*Triadica sebifera* (L.) Small] (Euphorbiaceae) is native to eastern Asia. Purposeful and accidental movement of this species over the past couple of centuries have resulted in its naturalization in many tropical, subtropical, and temperate areas in the world. In the southern U.S., Chinese tallowtree has proven to be one of the worst woody invasive plants in terms of shading out native vegetation, rapidly invading after disturbance or even invading previously diverse, undisturbed habitats. Researchers have discovered at least two promising candidates for classical biological control of Chinese tallowtree. Beekeeping organizations have raised objections to their release, as beekeepers prize the quality honey produced from an abundant spring nectar flow. We examine Chinese tallowtree's invasive characteristics and detrimental effects, as well as demonstrated or potential direct and indirect effects on native and non-native pollinators, in the context of proposed biological control efforts.

Comparing the role of propagule pressure in the colonization success of *Hylurgus ligniperda* and *Ips pini*

Kevin Chase[a,b], Dave Kelly[b], Andrew M. Liebhold[c], and Eckehard G. Brockerhoff[d]
[a] Bartlett Tree Experts, Charlotte, NC
[b] School of Biological Sciences, Centre for Integrative Ecology, University of Canterbury, Christchurch, New Zealand
[c] USDA Forest Service, Morgantown, VA
[d] Swiss Federal Institute for Forest, Snow and Landscape Research

A crucial factor affecting the colonization process of invading species is propagule pressure, the size and frequency of arriving populations. A key determinant contributing to propagule pressure effects on invasion success is the ‘Allee effect’, which is defined as increasing population growth with increasing abundance. We conducted parallel experimental releases using two species of bark beetles, *Hylurgus ligniperda* in New Zealand and *Ips pini* in North America, to (i) quantify colonization thresholds, (ii) empirically test for Allee effects, and (iii) assess the role propagule pressure in invasion success. Establishment success was positively associated with release density (i.e., propagule pressure) for both species but colonization success generally occurred at lower densities for *H. ligniperda* than for *I. pini*. We discuss the biological characteristics determining colonization success. Our results linking invasion failure to small founding population sizes generally support the theoretical literature on the role of propagule pressure and Allee effects in biological invasions.

Amitinol: A possible pheromone component for *Ips calligraphus* that is generated post-release.

Brian T. Sullivan[a], William P. Shepherd[a], and David Wakarchuk[b]
[a] USDA Forest Service, Southern Research Station, Pineville, Louisiana, USA
[b] Synergy Semiochemicals, Delta, British Columbia, Canada V4G 1E9

The bark beetle *Ips calligraphus* is a significant mortality agent of pines in the southeastern United States, although for the most part it attacks trees that have fallen or been weakened by disease, drought, or injury. Like many other bark beetle species capable of killing healthy trees when at high population densities, *I. calligraphus* releases an aggregation pheromone that concentrates attacking beetles on individual trees in sufficient numbers to overcome their constitutive defenses. In the early 1970s, this aggregation pheromone was identified as consisting of two components, the oxygenated monoterpenes ipsdienol and *cis*-verbenol (Renwick and Vité 1972). These are produced by attack-initiating male beetles shortly after entering the phloem, and the combination attracts both sexes. Lures for this species can be purchased from commercial sources for detection and monitoring purposes. No conspecific-produced attraction antagonists have been identified for this species.

The semiochemistry of *I. calligraphus* has not been investigated comprehensively. In particular, there have been no studies with coupled gas chromatography-electroantennographic detection (GC-EAD). In GC-EAD, individual compounds within a crude sample collected from a natural odor source are separated and then presented sequentially to the antenna of an individual insect. Voltage changes across the antenna coinciding with compound exposure indicate an olfactory stimulant, and these olfactory stimulants are subsequently identified by gas chromatography-mass spectrometry. The technique allows compounds in complex mixtures of natural odors to be screened rapidly for olfactory stimulants, and these can be subsequently tested for behavioral activity. We hypothesized that important semiochemicals mediating host colonization by *I. calligraphus* were still undiscovered.

We sampled the volatiles arising from individual gallery entrances of *I. calligraphus* males or mixed-sex groups on pine logs in the laboratory. Teflon funnels with a 4 cm-diameter mouth were placed over the entrances, and air was drawn from these through a cartridge of a chemical adsorbent (polydivinylbenzene). These samples included both insect- and host-produced odors associated with beetle attacks. Pentane extracts of the cartridges were analyzed on a GC-EAD with preparations of both male and female *I. calligraphus* antenna. Deflections of the EAD trace were registered to only three compounds: the known pheromone components ipsdienol and *cis*-verbenol as well as a third that was not previously reported in association with this species. This was amitinol, a close chemical analog of ipsdienol that has been identified in association with several other species of *Ips* bark beetle (Kohnle et al. 1988). Surprisingly, antenna of neither sex of *I. calligraphus* responded to the major host volatiles (hydrocarbon monoterpenes, e.g., *alpha*- and *beta*-pinene) despite their being present in high concentrations in the samples.

In further semiochemical sampling tests, we found significant amounts of amitinol in air arising from beetle attacks or frass, whereas extracts of male hindguts (where pheromone accumulates prior to release) and headspace samples of individual males excised from bark contained only trace quantities. This agrees with an earlier study, which suggested that amitinol can be produced through an apparently spontaneous structural rearrangement of ipsdienol in contact with phloem particles (the major constituent of beetle frass) (Kohnle et al. 1993). Our own preliminary tests appeared to confirm this observation. Although evidence suggests that amitinol is directly synthesized by some species of *Ips* (Francke 1980, Seybold et al. 1995), our results suggest that, in *I. calligraphus* at least, amitinol is generated from ipsdienol after the male has released it into the environment. Samples of male gallery entrances to which females were added sequentially indicated an increasing ratio of amitinol to ipsdienol with each female addition, although generally the levels of both compounds tracked each other closely. These progressive ratio changes in favor of amitinol suggested that the compound could be a cue indicating the degree of colonization of the host resource, and, as such, we suspected it might have attraction-inhibiting activity.

Field tests were conducted in which amitinol lures with two different release rates (approximately 0.1 and 1 mg/d) were placed on traps with *cis*-verbenol either alone or with ipsdienol. Lure treatments including both *cis*-verbenol and ipsdienol were highly attractive to *I. calligraphus*, however presence of the amitinol devices did not alter beetles' responses. Furthermore, combinations of amitinol and *cis*-verbenol alone were not more attractive than the *cis*-verbenol only control (which trapped very few insects). Lure discrimination was similar for both sexes. We also conducted a walking bioassay in which individual females were released on a wooden platform, which had four equidistant holes each containing a 3 mm-diam. segment of silicone tubing treated with test semiochemicals. For this study, amitinol was purified by preparative gas chromatography to remove all but traces of ipsdienol (>99.5% free of ipsdienol). We measured arrestment of the beetle over each hole during a 5 min interval, testing 61 insects in total. Treatments were *cis*-verbenol alone, with amitinol, with ipsdienol, or all three compounds. Ratios of these compounds mimicked those produced by insect attacks. As in the field trials, beetles responded strongly when ipsdienol was present, however, the further addition of amitinol (the three-component treatment) did not change the response. Amitinol significantly increased responses to *cis*-verbenol alone, but not to the level of either treatment which included ipsdienol. This result suggested the existence of some attractant/arrestant activity of amitinol with walking females.

Thus, we found no evidence to suggest that amitinol influences orientation of flying *I. calligraphus* to trees being infested by conspecifics, and we found limited evidence that it might influence mate finding by females post-landing. Our behavioral results do not support the hypothesis that amitinol could serve as an attraction inhibitor and attack density regulator (a function attributed to many bark beetle semiochemicals) for *I. calligraphus*. The apparent attraction of walking females to amitinol may be biologically irrelevant since this semiochemical in *I. calligraphus* does not occur in the absence of ipsdienol, which was far more attractive. Although our olfactory research succeeded in identifying a candidate for an additional *I. calligraphus* pheromone component, our studies failed to identify behavioral influences to which an ecological function could be attributed.

Gene silencing as a novel tool for emerald ash borer management

Flavia Pampolini[a] and Lynne K. Rieske[a]
[a] University of Kentucky, Department of Entomology

RNA interference (RNAi) is a molecular mechanism triggered by the introduction of double-stranded RNA (dsRNA) designed to induce gene knock-down; it is a promising technology with powerful potential for insect pest control. The RNAi pathway disrupts target genes and can lead to insect mortality when essential genes are silenced and subsequent protein synthesis is interrupted. Previous studies have demonstrated that the RNAi mechanism is functional in the highly invasive, tree-killing emerald ash borer (EAB) *Agrilus planipennis*. Both larvae and adults are sensitive to ingested and microinjected dsRNA, and suitable target genes for RNAi in EAB have been identified. Thus, this technology shows promise as a potential method for EAB management. However, two aspects stand as barriers to deployment of RNAi as a viable pest management approach: its specificity and practical delivery.

Our first study addresses specificity, and our subsequent research addresses delivery. The RNAi pathway involves the complementarity of ≥16 base pair sequences to the target genes in a given species or closely related species. This specificity minimizes any detrimental effects of an RNAi strategy to non-target organisms (NTOs). Nevertheless, to move a biopesticide using RNAi technology toward commercialization, its risk to the environment and possible adverse effects on NTOs must be evaluated. The Environmental Protection Agency suggests the risk assessment framework in use for genetic modified crops as a starting point to evaluate potential hazards for RNAi products and recommends investigating pest-specific dsRNA impacts in species that represent key functional groups of economic and ecological importance; this is the approach used here.

We evaluated the spectrum of activity of three dsRNAs targeting the genes hsp, shi and sn-rnp in EAB in model insects representing five functional guilds including herbivore (*Leptinotarsa decemlineata*), predator (*Coleomegilla maculata*), detritivore (*Reticulitermes flavipes*), pollinator (*Apis mellifera*), parasitoids (*Tetrastichus planipennisi* and *Spathius agrili*); the last represented by the classical biological control agents currently deployed for EAB management in North America. All NTOs were exposed to EAB-specific dsRNAs in diet bioassays that measured potential lethal effects. Gene expression and in silico analysis were also assessed on NTOs for which gene sequences were publicly available. Bioassays demonstrated no lethal effects on the model insects, suggesting a narrow spectrum of activity for the three EAB-specific dsRNAs evaluated. The gene expression analyses suggest potential sublethal effects on our model pollinator; however, we found no effects on insect survival. Overall, we found no nontarget effects of dsRNAs targeting the EAB genes in model insects and no effects on the classical biological control agents, confirming a high degree of specificity to the target insect.

Effective delivery of the dsRNA is challenging. Using labeled dsRNA coupled with confocal microscopy, we have demonstrated uptake of the labeled dsRNA in green, *Fraxinus pennsylvanica*, and tropical ash, *F. uhdei*, through root and/or petiole absorption. We inserted a fluorescing label into the exogenous dsRNA, exposed plant and insect tissues to the labeled dsRNA, and used confocal microscopy to evaluate its distribution in plant and insect tissues. Labeled dsRNAs were detectable in all ash tissues evaluated 48 h post-application, including root, stem, and leaf, and in insect tissues 8 d post-application. Additionally, adult EAB fed tropical ash leaves treated with EAB-specific dsSHI through petiole absorption experience significant knock down of the shi gene, and significant mortality.

Our findings provide a proof of concept that delivery of dsRNAs through topical or systemic application is feasible, but a practical delivery method remains elusive. Current efforts are focused on gaining a greater understanding of the spatial and temporal distribution of EAB-specific dsRNAs in ash seedlings, and in developing a host-induced gene silencing strategy generating resistant transgenic ash trees that express RNAi constructs targeting EAB-specific genes.

Effects of prescribed fire and forest age on pollinator diversity in the longleaf pine ecosystem

Michael D. Ulyshen[a], J. Kevin Hiers[a], Scott M. Pokswinksi[a], Audrey C. Wilson[a], Gunnar C. Ohlson[a], and Conor Fair[a]

[a] USDA Forest Service, Southern Research Station

There is much interest in preserving and restoring the remaining fragments of longleaf pine forest on the southeastern U.S. coastal plain. This endangered ecosystem is famous for its high diversity of fire-adapted plants and other organisms, but few efforts have been made to describe the associated bee community or to develop management recommendations for conserving this fauna. Results from three studies aimed at addressing these questions will be discussed. The first study found a positive relationship between pyrodiversity (i.e., heterogeneity of burn history on the landscape) and the diversity of both bees and butterflies. It also suggests that high burn frequency over large areas may have a negative effect on these insects. The second study found a higher concentration of ground-nesting bee nests in regularly burned forests than in forests burned less frequently. The third study found few differences in bee diversity between old-growth and mature secondary longleaf pine forests, suggesting that recovering forests can still support a high diversity of pollinators. In addition to establishing baseline knowledge about the bees of the longleaf pine ecosystem, this work will provide land managers with important information for protecting pollinators throughout much of the southeast.

Landscape and local factors driving species richness of longhorned beetles and bees in a fragmented landscape

Clayton R. Traylor[a], Michael D. Ulyshen[b], and Joseph V. McHugh[a]
[a] University of Georgia
[b] USDA-Forest Service, Southern Research Station

Insect communities respond to a variety of factors, ranging from local habitat conditions to processes operating at a landscape scale. Specific influences may vary between taxa that have different life histories or dissimilar resource requirements. Within forests, the diversity of saproxylic insects is often used as an indicator of overall forest health, and these species facilitate the decomposition of woody debris. In recent years, increased attention has also been given to pollinators in forests. Pollinators can obtain a variety of resources from forests, and they move between forests and other land uses. Yet, how these two groups respond to landscape factors in forests is relatively understudied. Here, we investigate how native longhorned beetle and bee diversity are affected by local forest conditions and landscape context. Longhorned beetles (Coleoptera: Cerambycidae) comprise a diverse family that mostly tracks fresh deadwood resources. Bees (Hymenoptera: Apoidea: *Anthophila*) are significant pollinators of native trees and forbs. We sampled these insects from forests in Athens, GA, along gradients of both forest age and landscape forest amount. Other local and landscape factors were also measured and included in the analysis. These relationships with species richness will be discussed along with implications for conservation.

STUDENT PAPERS

Student Paper Competition 1

Moderator: Jess Hartshorn[a]
[a] Clemson University

Following *Celtis laevigata* Willd. mortality and the commonly associated insects in the southeastern US

Emilee M. Poole[a], Michael D. Ulyshen[b], and Scott Horn[b]
[a] University of Georgia
[b] USDA Forest Service, Southern Research Station

Celtis laevigata Willd. (sugarberry) is a native tree commonly found along floodplains and rivers in the southeastern US. This species has been declining in the region since 2008, when reports were first made around Columbia, SC. Consistent symptoms are small yellow leaves, branch dieback, and premature leaf fall. A buprestid species, *Agrilus macer* LeConte, and a nonnative aphid, *Shivaphis celti* Das, are commonly associated with dying sugarberry. Efforts have been made to map the geographic range of areas with high mortality and investigate the associated insects to determine whether the species are causal agents. Although symptomatic trees are present throughout South Carolina and Georgia, our findings indicate *A. macer* is present in the southern United States, while most records centralize around Texas and Louisiana. This beetle is an opportunistic secondary pest on sugarberry but does not transmit harmful fungal pathogens. Future efforts to identify other contributing factors are underway as understudied, *S. celti*, is currently under investigation to determine its role in the mortality episode.

Disease-induced changes in bark structure and pathogen interactions impact host-insect-pathogen dynamics in the beech bark disease system

Ken Windstein[a], Eric Morrison[a], and Jeff Garnas[a]
[a] University of New Hampshire Dept. of Natural Resources and the Environment

Beech bark disease (BBD) arises from the interaction between American beech, an exotic scale insect, *Cryptococcus fagisuga*, and two species of *Neonectria* fungi. While the scale insect is a key facilitator of disease along its advancing front, the strength and nature of dynamic feedbacks between insects and fungi – particularly in the context of a variable tree response – are poorly understood in the BBD aftermath range. BBD development and severity is highly variable across time and space. We hypothesize that feedbacks between disease agents, principally indirect antagonistic effects mediated through BBD-induced changes in bark structure, are largely responsible for this variation, and so are important for understanding and managing BBD. We employed a field experiment implemented in the late summer and early fall of 2019 comprising an artificial challenge assay experiment applying two egg densities of *C. fagisuga* on 80 American beech, stratified by bark response type. On half of these trees, we inoculated *Neonectria faginata* and *N. ditissima* (and their combination) in 6mm agar plugs, also across scale insect densities and bark types. The results of both field experiments were

then assessed in late July 2020 to quantify scale insect establishment and fungal lesion growth. Preliminary results indicate that the area of necrosis caused by fungal inoculation growth is independent of initial scale insect density. Host bark structure, however, strongly affects fungal growth and scale insect colonization rate. Furthermore, lesion growth in the co-inoculation treatment was significantly reduced suggesting that these fungi may act as antagonists in the BBD system.

Translocation and persistence of dsRNA inducing gene silencing in southern pine beetle: prospects for tree protection

Zachary A. Bragg[a] and Lynne K. Rieske[a]
[a] Department of Entomology, University of Kentucky

Exogenously applied double-stranded RNA (dsRNA) can induce potent host specific gene knockdown and mortality in insects. RNA-interference (RNAi) has proven effective in silencing genes and causing mortality in forest pests responsible for catastrophic losses, such as the southern pine beetle (*Dendroctonus frontalis*) and its conspecific mountain pine beetle (*D. ponderosae*). Yet deployment of gene silencing technologies for pest suppression in forest systems is lagging. Multiple barriers stand between laboratory screening and deployment; one such barrier is development of an efficient delivery technique. Delivery through host plants could serve as an effective mechanism for introducing pest-specific dsRNA for tree protection, but an understanding of exogenous dsRNA movement and retention through plant tissues is essential. To evaluate the persistence and movement of dsRNA within coniferous woody tissue, loblolly pine (*Pinus taeda*) seedlings were exposed via a root soak to two dsRNAs, one of which was a southern pine beetle-specific dsRNA designed to cause insect mortality, and the other of which served as a dsRNA control. Seedlings were destructively sampled after exposure and divided into: roots, stems, needles, twigs with needles, and apical meristems. Total RNA was extracted from each tissue type; gel electrophoresis confirmed recovery of the exogenous dsRNAs, which were further verified using melt curve analysis and Sanger sequencing. I was able to confirm the presence of exogenous dsRNAs in each tissue type after 1d, 3d, 5d, and 7d of dsRNA exposure. Recovery of exogenous dsRNAs varied both spatially, with stem tissue yielding the most successful recovery, and temporally, with 24h time point having the most successful recovery. It's notable that the southern pine beetle-specific dsRNA was recoverable in stem tissue, the tissue where biological activity is most needed, up to 7 days following treatment. Current efforts are focusing on evaluating insecticidal activity and determining appropriate dosage. My findings suggest that application of exogenous dsRNAs via root drench could provide single-tree protection against the southern pine beetle and provide an additional tool for an integrated pest management program aimed at preserving tomorrow's forests.

Longleaf pine savanna after wind disturbance: management practices and lower stem and root feeding beetles and their associated blue stain fungi

Crystal Bishop[a], Kamal J. K. Gandhi[a], Kier D. Klepzig[b], and Caterina Villari[a]
[a] Warnell School of Forestry and Natural Resources, University of Georgia; Jones Center at Ichauway, Newton, GA
[b] Jones Center at Ichauway, 3988 Jones Center Drive, Newton, GA, 39870

Background

Bark beetles have important economic and ecological effects in forest systems. Especially after primary disturbance agents, such as hurricanes, they can exploit destabilizing events and colonize downed and stressed trees, not only feeding and reproducing in them, but also vectoring blue stain fungi. These fungi play a role in the decline of the health of pine trees by compounding initial damage from wind disturbance events (Zanzot et al. 2010). Blue stain fungi are typically weakly virulent fungi belonging to the order *Ophiostomatales* and are associated with many bark beetles (Harrington 2005, Jankowiak 2013, Kirisits 2007, Six and Wingfield 2011). Bark beetles and blue stain fungi are often associated in a symbiotic relationship. The beetle may benefit through nutrient accumulation and detoxification of tree defense metabolites via the fungus, thus creating a better environment for bark beetles to grow and reproduce, while the fungi gain the benefit of a vector to assist with dispersion (Biedermann and Vega 2020).

Hurricane Michael caused sixteen tornadoes and widespread rainfall ranging from 3 to 6 inches, damaging timber stands, forests, agricultural fields and building structures (Brett 2018). At our study site, this storm carried sustained winds of over 100 mph, broke off or knocked over thousands of trees, and left high amounts of coarse woody debris and stressed pine trees. However, management practices aimed at restoring forests to pre-wind disturbed conditions may mitigate the additional damage caused by beetles after storms. With this in mind, we endeavor to better understand how management may affect lower stem and root feeding beetles and blue stain fungi.

Objective

The goal of this study is to better understand how post-hurricane salvage management of longleaf pine affects pine root infesting beetles and weevils, as well as the blue stain fungi they carry. We have two main objectives: 1) analyze target beetle abundance across three different treatment types within a longleaf pine ecosystem and 2) characterize the blue stain fungi carried phoretically by the target beetles and analyze differences in species composition across these treatment types.

Methods

We chose the Jones Center at Ichauway as our field site: a nearly 12,000 ha longleaf pine ecosystem that was directly damaged by hurricane Michael in 2018. Staying strictly within longleaf pine stands, we established five plots within each of three different management treatments: (i) wind-disturbed (no active treatment); (ii) wind-disturbed with prescribed burning and salvage logging; and (iii) wind-disturbed with prescribed burning and no salvage logging. These treatments were chosen based on their applicability to the Jones Center and other neighboring forest lands.

To identify lower stem and root-feeding beetle abundance, we placed one Lindgren funnel trap in each plot. This trap was placed at least 50 m away from a road or fire break and was baited with polyvials (West Green Global Technologies) filled with ethanol and turpentine, along with an Exo-brevicomin lure (Synergy Semiochemicals). We are collecting from these funnel traps every two weeks, for two separate collection phases between April 2019 to April 2020 and August 2020 to August 2021. We will identify all collected specimens of lower stem and root feeding beetles to species. We anticipate finding target beetle species within the genera *Dendroctonus*, *Hylastes*, *Hylobius*, and *Pachylobius*.

We will also characterize blue stain fungi carried by the three beetle species found in highest abundance across all plots, which are *D. terebrans*, *H. pales*, and *P. picivorus*. We captured these beetles alive using two different types of traps: billet traps for root feeding beetles and milk jug traps for the lower stem beetles. Billet traps consist of a longleaf pine log, buried 100 cm underground to attract root feeding beetles (Flechtmann et al. 1999). To increase attractiveness of longleaf pine logs to the beetles, we removed four 2 cm^2 patches of bark before the log was buried. We collected catches from billet traps once per week. Milk jug traps are empty inverted milk jugs with the bottoms removed that are baited with ethanol and turpentine so the beetles can fly into and funnel down to the neck of the bottle to be collected. We used the milk jug traps to collect *D. terebrans* (Klepzig et al. 1991) and collected from them every other day. Both traps were set out for collection at peak flight season for the targeted species and trapping continued untill three beetles of each species per plot was collected alive. Once target beetles were collected, we plated them using a serial dilution technique to quantify and isolate blue stain fungi. We washed each beetle in 1 mL of 1% tween 80 solution and sterile water and plated them out in dilutions of 1X, 10X, and 100X each in triplicate onto malt agar amended with 200ppm cycloheximide and 100ppm streptomycin (CSMA) (Zhou et al. 2007, Harrington and Fraedrich 2010). We incubated the plates at 19° C for one week to allow for colony growth and then counted the number of growing colonies. Individual colonies were morphologically categorized, and representatives of each category were then isolated. Colonies that have been morphologically distinguished as blue stain fungi will be identified to species through PCR and Sanger sequencing of the beta tubulin (βt) and elongation factors (EF) gene regions, which have been shown to better discriminate between Ophiostomatales species than the Internal Transcribed Spacer (ITS) region (Duong et al. 2015, Duong et al. 2012, Glass and Donaldson 1995, Stielow et al. 2015).

Findings

We have completed one full year of beetle abundance collection for 2019 to 2020 and are currently analyzing the data, while year two is being collected. For objective two, we have collected and completed the plating of two of the three target species, *H. pales*, and *P. picivorus*, and we are currently processing the obtained colonies for their molecular identification. We are also still plating *D. terebrans* specimens. Thus far, we have identified one species, *L. procerum*, which was isolated from both *P. picivorus* and *H. pales*. Within the next 6 months, we plan to complete the second full year of beetle abundance collection and to complete the identification of the fungal species associated with our target beetles.

Keywords: bark beetles, hurricane, blue stain fungi

Acknowledgements: This work is supported by the USDA National Institute of Food and Agriculture, McIntire Stennis project #GEOZ0193-MS, The Jones Center at Ichauway, and the D. B. Warnell School of Forestry and Natural Resources. Additional help is provided by the forest entomology/microbiology lab at the Jones Center at Ichauway.

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SPB-specific gene silencing has no effect on nontarget insects

Hannah Hollowell[a] and Lynne K. Rieske[a]
[a] Department of Entomology, University of Kentucky, Lexington, KY

The southern pine beetle (SPB) (*Dendroctonus frontalis*) has been the most destructive forest pest of the southeastern United States for decades. Fortunately, RNA interference (RNAi), an emerging molecular pest suppression technology, shows promise for its management. RNAi is a cellular antiviral pathway triggered by exogenous double-stranded RNA (dsRNA), inhibiting the expression of targeted genes and preventing key cellular functions, thereby inducing mortality. By carefully designing dsRNAs specific to essential genes in SPB, we can trigger the RNAi pathway, silence target genes, and kill beetles. But demonstrating the specificity of this approach is essential to its deployment. The Risk Assessment framework developed by the Environmental Protection Agency recommends investigating the effects of pest-specific dsRNAs on nontarget insect species that represent key functional groups of economic and ecological importance.

Through feeding bioassays evaluating SPB-specific dsRNAs on nontarget insects, I assessed potential lethal and sublethal effects on selected model and pine-associated insects. Nontarget insects were fed 10 ug of SPB-specific dsRNAs daily for 3 d and evaluated. There was no effect of the SPB-specific dsRNAs on survival in the pine-associates *Ips calligraphus* ($p>0.05$) or *Neodiprion lecontei* ($p>0.05$), and additionally no sublethal effects were observed for *N. lecontei* when evaluated for larval weight gain ($p>0.05$). For the predatory model insect *Coleomegilla maculata,* no effects were found on survival, larval weight gain or fecundity ($p>0.05$). Survival as well as food consumption of a model detritivore, *Reticulitermes flavipes,* were also not affected ($p>0.05$). For both *C. maculata* and *R. flavipes*, gene expression analyses using RT-qPCR revealed no significant changes in relative gene expression in the SPB-specific dsRNA treatments ($p>0.05$). I plan to also conduct gene expression analyses for the pine-associates to gain a full understanding of potential nontarget effects of this innovative approach to SPB management. These findings are crucial to helping ensure the safety of deploying SPB-specific dsRNAs in forests and provide hope for the addition of gene silencing as a tool in IPM.

Oystershell scale: the awakening of a sleeper species in the southwestern US

Connor D. Crouch[a], Amanda M. Grady[b], Nicholas P. Wilhelmi[b], Richard W. Hofstetter[a], Daniel E. DePinte[b], and Kristen M. Waring[a]
[a] School of Forestry, Northern Arizona University, Flagstaff, AZ
[b] Forest Health Protection, Arizona Zone, USDA Forest Service, Flagstaff, AZ

Quaking aspen (*Populus tremuloides*) is the most widely distributed tree species in North America (Little 1971) and is a keystone species in the conifer-dominated western United States (Campbell and Bartos 2001). Aspen provides habitat for an array of plants, animals, and invertebrates (DeByle 1985) and makes a disproportionately large contribution to biodiversity compared to the relatively small area it occupies on the landscape (Chong et al. 2001; Kuhn et al. 2001). Aspen stands also provide a variety of ecosystem services, including significant contributions to carbon sequestration (Woldeselassie et al. 2012) and water yield potential (LaMalfa and Ryle 2008). From a human-oriented standpoint, aspen contributes to revenue generated from hunting, tourism, and recreation (McCool 2001; Rogers 2017) and has cultural and aesthetic value as an iconic tree species of the American West (Assal 2020).

The emergence of an invasive insect, oystershell scale (*Lepidosaphes ulmi*; OSS), threatens conservation of aspen in the southwestern US (Crouch et al. 2021). Although OSS's origin is uncertain, the species was likely introduced to North America by European settlers in the 1700s (Howard 1894; Miller et al. 2005). Since its introduction three centuries ago, OSS is now present throughout North America (Tothill 1919, Ciesla 2011) and is a common pest of many deciduous tree species, including aspen, in urban settings (Ciesla 2011, Cranshaw 2013). Although OSS is polyphagous and pervasive in North America, it has not been a major pest in natural forest settings (Ciesla 2011). However, OSS has recently spread into natural aspen stands in northern Arizona, where outbreaks are causing dieback and mortality of aspen (Crouch et al. 2021).

Species invasions typically follow a pattern consisting of three stages: arrival, establishment, and spread (Liebhold et al. 1995). During the arrival phase, a species immigrates into new areas beyond its native range. The second phase, establishment, occurs after the species arrives in the new location and requires a population to be persistent in the new location. Following establishment, a population may be constrained by environmental variables that restrict population growth. However, if the population thrives in the new location, it progresses to the spread phase of invasion as it experiences rapid population growth and widespread geographic expansion (Liebhold et al. 1995). We hypothesize that OSS is a sleeper species that has recently awoken and entered the spread phase of invasion in northern Arizona (Crouch et al. 2021).

Sleeper species are unique among other invasive species because their populations remain at slow growth rates for long periods of time prior to experiencing widespread expansion (NRC 2002). We hypothesize that OSS is a sleeper species because it has been in North America for three centuries, but until recently, it was not a concern in natural forest settings. It is unclear which factor(s) led to the awakening of OSS, but an increasingly arid climate is a likely explanation. There are two potential ways in which recent climatic changes may have led to the ongoing outbreaks of OSS. Aspen in this region is under increasing environmental stress from a warming climate (Zegler et al. 2012), and such stress increases the susceptibility of aspen to insects and diseases (Marchetti et al. 2011). Therefore, weakened host defenses may have

allowed OSS to experience increased population growth. On the other hand, a warmer climate may have directly improved conditions for OSS population growth by increasing the species' fitness and abundance. Temperature changes that have already occurred may have enabled OSS's awakening in natural aspen stands, and in the future, warmer temperatures at higher elevations and latitudes may promote further spread of OSS. The former would threaten the largest, healthiest aspen stands in northern Arizona, which occur at higher elevations, and the latter would threaten the rest of aspen's range in the western US.

Keywords: invasive species, *Lepidosaphes ulmi*, *Populus tremuloides*

Acknowledgments: Partial support for this work was provided by the McIntire-Stennis Cooperative Forestry Research Program and Northern Arizona University's Presidential Fellowship Program. Suppression funding for monitoring and OSS treatment implementation was provided by USDA Forest Service, Forest Health Protection, Southwestern Region, Arizona Zone. We are immensely grateful for contributions and field support provided by Al Hendricks, Kyle Price, and staff on the Coconino, Kaibab, Prescott, and Apache-Sitgreaves National Forests. We would also like to thank Margaret Moore for helping us develop the conceptual basis for this work.

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Impacts of a catastrophic hurricane on subcortical beetle populations in southern pine stands

Seth Spinner[a], Brittany F. Barnes[a], Elizabeth McCarty[a], and Kamal J.K. Gandhi[a]
[a] D.B. Warnell School of Forestry & Natural Resources, University of Georgia

The pine forests of the southeastern U.S. are among the most productive in the world (Hanson et al. 2010). Catastrophic wind disturbance events, such as hurricanes, are major agents of ecosystem disruption in southeastern U.S. forests (Vogt et al. 2020). These storms can cause damages to trees, such as uprooted stems and broken branches, stems, and crowns (Gresham et al. 1991). These injuries can lead to tree mortality (Vogt et al. 2020). Bark beetles (Coleoptera: Curculionidae: Scolytinae) frequently invade wind-disturbed stands to exploit the high numbers of weakened or recently killed trees and influx of coarse woody debris (Connola et al. 1956; Gardiner 1975; Grimbacher and Stork 2009; Nikolov et al. 2014). Hurricane damage is typically heterogenous across impacted regions due to landscape characteristics like topography, soil traits, stand conditions, and local meteorological factors like the proximity of a stand to the eye of the hurricane (Foster and Boose 1992; Mladenoff et al. 1993). Damage heterogeneity may influence bark beetle population patterns across the landscape. Hurricane intensity is increasing due to global climate change, leading to disturbances that may exceed the resiliency of these ecosystems and cause economic losses outside of the historical norm (Senevirante et al. 2012).

Hurricane Michael made landfall near Mexico Beach, Florida on October 10, 2018, and caused catastrophic damage to forests in Georgia and Florida (Beven et al. 2018). In these two states alone, this storm damaged approximately two million hectares of forests, resulting in nearly $2 billion in economic losses (Florida Forest Service 2018; Georgia Forestry Commission 2018). Due to the nature of forest damage caused by Hurricane Michael, bark beetle populations may increase in number across the landscape at different rates depending on the severity of storm damage exhibited in different stands. These patterns may lead to complicated management situations for foresters and cause further economic damages. Salvage harvesting may allow foresters to recover some timber value following hurricanes that would otherwise be lost while reducing the amount of resources available to bark beetles. However, there are often many constraints that prevent forest managers from salvage harvesting immediately after a wind disturbance (Broman et al. 2009). Foresters must make tough decisions following catastrophic hurricanes regarding the timing and prioritization of salvaging operations in hurricane-damaged stands. Unfortunately, there has been little to no research into the responses of bark beetles to catastrophic wind disturbance in southern pine forests to inform foresters and landowners engaging in post-hurricane management.

The research objectives are to determine if bark beetle populations will change in numbers over a two-year period and if these changes will differ across various damage levels in southern pine forests. Results from this study will provide foresters with critical information regarding the timing of salvage logging in sites that exhibit different levels of hurricane damage to minimize economic losses from subsequent bark beetle infestations. Bark beetle sampling was conducted between May and September of 2019 and 2020 using Lindgren funnel trap baited with ipsenol, ipsdienol, and cis-verbenol and flight intercept panel traps baited with ethanol and alpha-pinene. We sampled fifteen loblolly pine-dominated stands that experienced 20-70% basal area loss in the Florida Panhandle region. Samples were collected every two weeks and *Dendroctonus terebrans, Ips avulsus*, *I. calligraphus*, and *I. grandicollis* from trap catches were identified and counted. Preliminary results from May-June 2019 indicated that bark beetles were the most numerous in trap catches in stands that experienced 20% damage and least numerous in trap catches in sites that experienced 21-40 % loss. This may indicate greater diversity and availability of host resources in the least damaged pine sites. The final results will help foresters make decisions regarding the timing of post-hurricane forest management activities as based on damage levels.

Acknowledgements: We would like to thank Joshua Barbosa, Ray Sharp, Chelsea Miller, and Sarah Klinect for the assistance with this project. We would also like to thank the D.B. Warnell School of Forestry and Natural Resources in the University of Georgia and private forestry companies for providing funding for this research project.

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Student Paper Competition 2

Moderator: Deepa Pureswaran[a]
[a] Natural Resources Canada, Canadian Forest Service, Quebec

Phytochemical response of loblolly pine (*Pinus taeda*) to southern pine beetle (*Dendroctonus frontalis*) symbiotic fungi

John de Soto[a], Kamal J.K Gandhi[b], Kier Klepzig[c], Brian Sullivan[d], and Caterina Villari[b]
[a] Department of Plant Pathology, University of Georgia, Athens, GA
[b] D.B. Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA
[c] The Jones Center at Ichauway, Newton, GA
[d] Southern Research Station, United States Department of Agriculture, U.S. Forest Service, Pineville, LA

Background

The production of secondary metabolites by pines and other conifers can be an effective defensive strategy against bark beetles including southern pine beetle (SPB) and associated fungi (Paine et al. 1997) and may also impact competition among their fungal symbionts.

Secondary metabolites of pines are comprised of terpenoids and phenolics, and a number of studies have investigated terpenoids and their role in the loblolly pine/SPB system (e.g., Franceschi et al. 2005; Hodges et al. 1979). However, the composition of phenolics, their composition in loblolly pine and their potential defensive role have yet to be fully understood. This discrepancy in the understanding of the two classes of compounds might be attributable to the widely-held belief that phenolics are more important in tree defense against fungi than insects, whereas research has focused on the latter (Witzell and Martin 2008). A deeper investigation of the host phenolics in the loblolly pine/SPB system is important because phenolics may strongly impact the SPB mutualistic fungi, which are essential for the reproduction of the SPB. Further investigation of the mechanisms underlying the interrelationships among the fungal symbionts may also shed additional light on the system's internal complexities. Of particular interest is the host's interaction with the antagonistic fungal associate *Ophiostoma minus*. It may both trigger a defense response in the host and counteract the response (Hemingway et al. 1977), and this defense response may be more toxic to SPB mutualists than to *O. minus*. These non-pathogenic species, in fact, cannot degrade, catabolize, the host response themselves, and this might give *O. minus* a competitive advantage over the mutualistic fungi. We hypothesize that *O. minus* induces a defense response in loblolly pine that is more detrimental to *Ceratocystiopsis ranaculosus* and *Entomocoricium cobbii* (the two mutualistic fungi associated with SPB) than to *O. minus* itself.

Objective

The objective of this study is to determine the changes in the phenolic and terpenoid profile of loblolly pine induced by inoculation with the three SPB associated fungal species.

Methods

In a three-week trial in fall 2020, we selected 50 mature trees from an even-aged 44-year-old stand of loblolly pines in Area 51 of Whitehall Forest, Clarke and Oconee counties, Georgia. We avoided trees with visible signs of damage, stress, insects or pathogens, and recorded diameter at breast height (DBH), percentage canopy cover, bare ground, woody shrubs, and graminoids within a four-meter radius for each tree selected. We adopted a stratified random sampling design with 10 blocks, each split into two strata. Within each stratum, we then chose five trees and randomly assigned them to one of the five treatments: (i) inoculation with *C. ranaculosus*, (ii) inoculation with *E. cobbii*, (iii) inoculation with *O. minus*, (iv) mechanical wounding, and (v) unwounded control. For inoculations, we removed four plugs of outer bark and phloem from four cardinal points using a 7 mm cork borer at 1.5 m height on the bole of each tree and replaced each removed plug with a similar sized phloem plug previously sterilized and then colonized with the selected fungal species, covering each inoculation point with duct tape (Villari et al. 2012).

We analyzed plugs removed at the beginning of the experiment (time T_0) to measure constitutive secondary metabolites. Three weeks after tree inoculation (T_1) we measured the length of lesions in the sapwood and took phloem samples from the edge of symptomatic tissue using a 7 mm cork borer. We measured the induced levels of secondary metabolites in these tissues. We used a subsample of these tissues to re-isolate the fungi and confirm success of the inoculation. At T_1, we also collected samples from untreated controls. We pooled samples from each plant, flash froze them in liquid nitrogen and stored them at -80 °C until further processing. We identified and quantified phenolic compounds via ultra-high-performance liquid chromatography, following the protocol described in Lopez-Goldar et al. (2018), and we will identify and quantify terpenoids via gas-chromatography mass-spectrometry, following the protocol described in Keefover-Ring et al. (2016). We will analyze data with a non-metric multidimensional scaling (NMDS) approach using the PC-ORD software, in collaboration with Dr. Paul Severns, Department of Plant Pathology, University of Georgia.

Main findings

The study is still ongoing, but our preliminary results indicate that lesions were significantly longer for the *O. minus* inoculated trees than those inoculated with mutualists *C. ranaculosus* and *E. cobbii* or receiving mechanical wounding. Additionally, we re-isolated *O. minus* from every tree inoculated with this species, but neither mutualist was re-isolated from any inoculated tree. This was not unexpected given the first species is a moderately virulent pathogen and the other two are non-pathogenic mutualists. A preliminary analysis of the phenolic data showed that the response was similar among the two mutualists and the wounded treatments, but different for *O. minus*. These results are incomplete, as we are still in the process of analyzing the terpenoid response of the tree to obtain a comprehensive understanding of the fungal induced response of loblolly pine to SPB associated fungi.

Keywords: chemical ecology, southern pine beetle, fungal associates, loblolly pine, secondary metabolites

Acknowledgements: This work is supported by the D. B. Warnell School of Forestry and Natural Resources, and by the Department of Plant Pathology, University of Georgia.

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Identifying attractive semiochemicals for *Anisandrus maiche* (Stark)

Kelsey Tobin[a] and Matthew Ginzel[a]
[a] Purdue University, West Lafayette, IN

Anisandrus maiche Stark (Coleoptera: Curculionidae: Scolytinae), an exotic ambrosia beetle native to Asia, has been spreading throughout the eastern United States since 2005. In the current invaded range, its preferred host plants are not well known, however, *A. maiche* has been found establishing galleries in plantation-grown black walnut (*Juglans nigra)* and nearby forested land in northwestern Indiana. It is difficult to predict the impact *A. maiche* could have on North American forests.

In this study, we conducted field-based trapping experiments in northwestern Indiana to explore the potential of ethanol and conophthorin as semiochemical attractants for *A. maiche*, as well as verbenone as a repellant. *A. maiche* capture in ethanol baited traps was significantly higher (p<0.001) than any other treatment group. These findings demonstrate bottle-traps

baited with ethanol are useful in monitoring for *A. maiche*, and aid stakeholders in establishing effective management programs. Furthermore, it appears that conophthorin repelled *A. maiche* in our study, suggesting that semiochemicals may hold promise for manipulating the behavior of this species using a push-pull strategy to protect high-value plantings of black walnut from attack.

Keywords: Coleoptera, Curculionidae, Scolytidae, *Anisandrus maiche*, exotic species, semiochemicals

A novel use of protein immunomarking in studying the dispersal of woodboring beetles

Scott Gula[a], Vanessa M. Lopez[b], Ann M. Ray[c], Scott A. Machtley[d], James R. Hagler[d], and Matthew D. Ginzel[a]
[a] Perdue University, West Lafayette, IN
[b] USDA Forest Service
[c] Xavier University, Cincinnati, OH
[d] USDA ARS, Maricopa, AZ

Invasive woodboring beetles are among the most destructive pests of natural and managed forests worldwide. The success of eradication efforts and quarantines to limit the spread of incipient populations of these pests is dependent on understanding their dispersal behavior. Most previous dispersal research involved capturing or rearing beetles en masse, marking them in the laboratory, releasing them in the field, and capturing them again. This process is labor intensive, time consuming, expensive, and human handling during the application of the mark can affect the behavior of the insects. There is a critical need for an affordable, efficient, and non-invasive marking technique to improve research on woodborer dispersal. We tested the efficacy of protein immunomarking for use in understanding the dispersal of woodboring beetles. Specifically, we tested the extent to which a protein mark adheres to the cuticle of emerald ash borers (*Agrilus plannipennis* Fairmaire) (Coleoptera: Buprestidae) as beetles emerge from protein-treated logs. This method has several advantages over traditional techniques including a low cost for both the protein and ELISA used to detect the protein, no need for mass rearing or capture, and the minimization of handling and disturbance to the beetles. In addition, we tested the extent to which proteins transfer from marked to unmarked beetles as well as the efficacy of various trapping methods. This novel use of protein immunomarking has potential as an effective and reliable marker for use in mark-capture and dispersal studies with buprestids, as well as other woodborers such as cerambycids and scolytids.

Evaluating RNAi-mediated gene silencing for suppression of *Ips calligraphus*

Mary Wallace[a] and Lynne K. Rieske[a]
[a] University of Kentucky

RNA interference (RNAi), or gene silencing, is a naturally occurring cellular antiviral response. By manipulating the pathway through the introduction of carefully designed exogeneous double stranded RNA (dsRNA), we can trigger the pathway, silence essential genes, and induce mortality. Inducing mortality in a target insect with minimal non-target effects makes this technology advantageous in integrated pest management programs. Thus, RNAi is emerging as a promising pest management strategy, and is already being implemented in agriculture. Efficacy has also been shown in several forest pests, and susceptibility to RNAi in other scolytines makes it a promising management tool for *Ips calligraphus*, the six-spined ips.

Ips calligraphus is a native North American bark beetle that, due to increasingly frequent and severe disturbance events, has become progressively more eruptive, with economic and ecological consequences in both its native and introduced ranges. Through direct feeding damage and the introduction of harmful microorganisms, *I. calligraphus* can kill most native pine species, including economically important species like loblolly (*Pinus taeda*) and shortleaf (*P. echinata*). While healthy trees can typically mount a successful defense to *I. calligraphus* attack, once beetles reach a rapid reproductive rate due to an abundance of suitable host material, densities can increase to a level at which even healthy trees can be successfully infested. This leads to widescale ecological and economic damage. Given the limitations of current management techniques in preventing these outbreaks, the potential for use of RNAi in this system as an additional IPM strategy is promising.

To evaluate the potential for triggering the RNAi pathway in this species through the introduction of exogenous dsRNA, adult beetles were fed a dsRNA solution designed to silence specific essential genes. These beetles were then evaluated for mortality compared to a negative control of dsGFP, green fluorescent protein, a gene not present in insects and unable to be silenced. I found evidence for activation of the RNAi pathway in the mortality assays, being able to induce significant mortality in target dsRNA treated beetles. I have validated reference genes for *I. calligraphus* that are stably expressed across varying abiotic and biotic conditions, including dsRNA treated beetles, and am currently evaluating gene expression via qPCR. This is the first study to investigate the feasibility of gene silencing via exogenous dsRNA in any *Ips* species, and these finding are relevant to the use of this technology in congeneric species. My finding are an important step toward developing this technology as an additional tool for IPM.

Predictors of mountain pine beetle dispersal in western Montana

August C. Kramer[a] and Brian H. Aukema[a]
[a] University of Minnesota

Mountain pine beetle is an irruptive forest insect and disturbance agent in pine forests of western North America, infesting almost all western pine species. Past outbreaks have killed tens of millions of acres of mature pines across the western United States. In spite of abundant work on the insect's ecology and tree killing capability, little is known about dispersal dynamics that are important to understand given potential threats of range expansion to pine forests of eastern North America. We exploited a recent outbreak from 2000 to 2015 in Montana that resulted in approximately six million acres of pine mortality to investigate how many fewer mountain pine beetles would be captured at distances farther away from active infestations. In the summer of 2020, we placed twenty baited Lindgren funnel traps along a 180-mile transect through western Montana from areas with established populations of mountain pine beetle to areas with no visible active infestations. Weekly collections were made from 4 August to 26 August. High numbers were captured at sites with no apparent proximate active infestations, and numbers varied weekly. While source populations cannot be confirmed, capture patterns away from pine forests can provide some insight into dispersal pressure given aerial and ground survey data.

Forecasting overwintering mortality of *Spathius galinae* in North America

Jacob T. Wittman[a], Brian H. Aukema[a], Jian J. Duan[b], and Robert C. Venette[c]
[a] University of Minnesota
[b] USDA Agricultural Research Station
[c] USDA Forest Service

Matching classical biological control agents to appropriate environments for introduction is necessary to optimize their release and performance. We evaluated the cold hardiness of the parasitoid *Spathius galinae* Belokobylskij & Strazanac, a classical biological control agent of emerald ash borer (*Agrilus planipennis* Fairmaire) in North America. We measured supercooling points and lower lethal (i.e., mortality) temperatures of cold acclimated, late-instar *S. galinae* larvae in controlled cooling assays in the laboratory. The average supercooling point of *S. galinae* larvae was -25°C. Most *S. galinae* died after reaching their supercooling point, although several larvae initiated freezing but later successfully eclosed. The presence of larvae that eclose after initiating freezing suggest that some individuals may be partially freeze tolerant. We also monitored development of mature (cocooned) *S. galinae* larvae in ash segments above and beneath the snow in three locations in Minnesota in the winter of 2019–2020. Larvae that were exposed to -29°C exhibited nearly 100% mortality. We forecast eclosion rates of *S. galinae* across the range of *Fraxinus* spp. in North America based on minimum winter temperatures using models developed from these data. Our results indicate that a high proportion of *S. galinae* may survive in areas where minimum winter temperatures reach as low as - 28°C. In areas where temperatures reach lower than -28°C, *S. galinae* will likely exhibit extensive mortality although a small portion of the population may survive and persist.

Student Paper Competition 3

Moderator: Jeff Garnas[a]
[a] University of New Hampshire

Preference of *Geosmithia morbida* for low wood moisture content may explain historical outbreaks of thousand cankers disease and predict future fate of *Juglans nigra* within its Native Range

Geoffrey M. Williams[a] and Matthew D. Ginzel[a]
[a] Perdue University, West Lafayette, IN

Given its influence on emergent threats such as thousand cankers disease (TCD), climate change should be a key consideration in the assessment of risks to resources such as the high-value hardwood, *Juglans nigra*. TCD is caused by *Geosmithia morbida* and its vector, *Pityophthorus juglandis*. The success of mutualisms between fungi and bark beetles is likely to be limited by competition with other fungi that are better adapted to the physicochemical conditions of their substrate. These conditions are in turn subject to climatic variation. In particular, wood moisture content is an important factor in fungal competition, and therefore could help determine environmental suitability for thousand cankers disease. We conducted competition experiments in *J. nigra* wood that was naturally or artificially colonized by *G. morbida* and other fungi over a range of equilibrium wood moisture content expected across prevailing U.S. climatic conditions. *Geosmithia morbida* consistently and successfully outcompeted other fungi at very low (< 5%) equilibrium moisture content. However, *Aspergillus* spp., known pathogens of bark beetles, outcompeted *G. morbida* when colonizing low-moisture wood from Indiana. We also fit a logistic regression model to the results of the competition experiments to predict survival of *G. morbida* across the U.S. based on expected wood moisture content. Expected survival of *G. morbida* was highest in historical TCD epicenters and partly explained the low incidence and severity of TCD in the eastern U.S. Our results also predict that under future climate scenarios, the area impacted by TCD will expand into the native range of *J. nigra*.

Evaluating the effects of regional drought and forest management on invasive *Sirex noctilio* congener, *Sirex nigricornis*

Kendra E. Wagner[a], Robert Jetton[c], Jess Hartshorn[b], Dimitrios Avtzis[d], and John J. Riggins[a]
[a] Mississippi State University
[b] Clemson University
[c] North Carolina State University
[d] Forest Research Institute, Vassilika, Greece

The European woodwasp (*Sirex noctilio* Fabricius) was detected in North America in 2004. Thus far in North America, *S. noctilio* has not caused major tree mortality, despite its ability to cause >70% mortality in poorly managed stands throughout the Southern Hemisphere. Forest management practices (i.e. harvesting, stand density, etc.) significantly reduce *S. noctilio* related mortality, except for during significant drought years. Although not currently classified as invasive in North America, *S. noctilio* exhibits eruptive population dynamics. These populations often remain at low population levels for up to 12 years before reaching outbreak populations, therefore it should not yet be disregarded as a significant forest pest in North America. The objectives of this study are to determine how drought conditions and basal area interact to influence native woodwasp abundance and to develop forest management recommendations to minimize outbreak potential of their conger *Sirex noctilio*. A cross-hatched log stack and Lindgren funnel trap was used to sample siricid populations. Treatments included thinned and unthinned pine plantations in drought and non-drought stressed areas in Mississippi, North Carolina and Ontario, Canada. We found that drought-stressed areas presented higher woodwasp capture, but that basal area had no effect. These results may advise forest management as *Sirex noctilio* increases its range to the southeastern US.

Community assembly of subcortical beetles and their associates on lightning-struck longleaf pine trees

Benjamin M. Gochnour[a], Tom Sheehan[a], Kier D. Klepzig[b], and Kamal J. K. Gandhi[a]
[a] University of Georgia
[b] The Jones Centre at Ichauway, Newton, Georgia

Cloud-to-ground lightning strikes are a widespread and rapid disturbance that causes tree damage and mortality in southeastern forest ecosystems. Tree damage by these strikes can create hotspots for bark and woodboring beetle (Coleoptera: Curculionidae; Buprestidae and Cerambycidae) populations, especially pest species, and may sustain them between outbreak events. The spatial and temporal structure of bark beetle populations and their associated predators and parasitoids may be sustained by lightning-struck trees, as these colonization events are discrete, periodic, ephemeral, and self-propagating. Our research objectives were to: 1) characterize the assembly of subcortical beetles and their associates arriving at lightning struck longleaf pine trees; and 2) assess intrinsic and host variation in insect colonization dynamics. In summer 2020, detonation cord wrapped around the tree trunks of six longleaf pine (*Pinus palustris*) trees was used to simulate lightning strike trauma. Lindgren funnel traps, hung at several heights along the tree's trunk, were used to monitor flight and arrival activity around the tree (both before and after detonation). Three trees were cut down and logs placed in emergence chambers to examine colonization success from sections of the tree trunk associated with the funnel traps. We determined arrival order of insect species and their numbers, flight height, and colonization height. Currently, we are identifying adults to species-level, and results will be analyzed using mixed linear models. Results of this study will contribute to better understand the assembly of insect communities centered on lightning, an important and common ecological disturbance agent during storm events.

Change in fuel loads following severe drought and bark beetle outbreaks in the central and southern Sierra Nevada

Crystal S. Homicz[a], Leif A. Mortenson[b], Beverly M. Bulaon[c], and Christopher J. Fettig[b]
[a] Department of Entomology and Nematology, University of California, Davis, CA
[b] USDA Forest Service, Pacific Southwest Research Station, Davis, CA
[c] USDA Forest Service, Forest Health Protection, Sonora, CA

The disturbance ecology of many conifer forests in western North America has deviated drastically from historical conditions largely as a result of fire suppression, extreme drought events, and bark beetle outbreaks. These deviations were exemplified in 2012–2015 when the worst drought in over a millennium occurred throughout parts of California. During and following the drought, a western pine beetle (*Dendroctonus brevicomis*) outbreak occurred in the central and southern Sierra Nevada causing severe (>90% in some areas) ponderosa pine (*Pinus ponderosa*) mortality (Fettig et al. 2019). The objectives of our study are to determine changes and variations in fuel loading over time, and to determine predictive variables of fuel loading following the outbreak.

A network of 180 11.3-m fixed-radius plots were established to monitor tree mortality levels, changes in tree species composition, and changes in fuel loading across three elevation bands on the Eldorado, Stanislaus, Sierra and Sequoia National Forests (914–1219, 1219–1524 and 1524–1829m on the Eldorado, Stanislaus, Sierra; 1219–1524, 1524–1829, and 1829–2134m on the Sequoia) (Figure 1). Fuels data across the plot network were measured in 2017 and 2019 using modified Brown's transects, and measurements will be repeated in 2021 and 2023. Preliminary data show total surface fuel loading has increased from 2017 to 2019 across all national forests and elevation bands, with the largest increase on the Sierra National Forest (Figures 2 and 3). Increases in surface fuel loading was similar across the three elevation bands 1000-hour fuels increased more than any other fuels class and little change was observed in litter and duff. Formal statistical analyses will follow fuels remeasurements in 2021 and 2023.

Previous studies predicted the highest rates of surface fuel accumulation to occur 11 to 20 years following a bark beetle outbreak in mixed-conifer forests in the Sierra Nevada (Stephens et al. 2018). However, observed snag fall rates and surface fuel accumulation on the plot network far exceeds previous predictions. Better understanding of changes in fuel composition following bark beetle outbreaks in Sierra Nevada forests provides important context for land management decisions, especially as outbreaks are likely increase in frequency and severity in the future.

Figure 1. Distribution of plots across the Eldorado National Forest (green), Stanislaus National Forest (black), Sierra National Forest (yellow) and Sequoia National Forest (red) (n = 45 per national forest), California, U.S. Figure from Fettig et al. (2019).

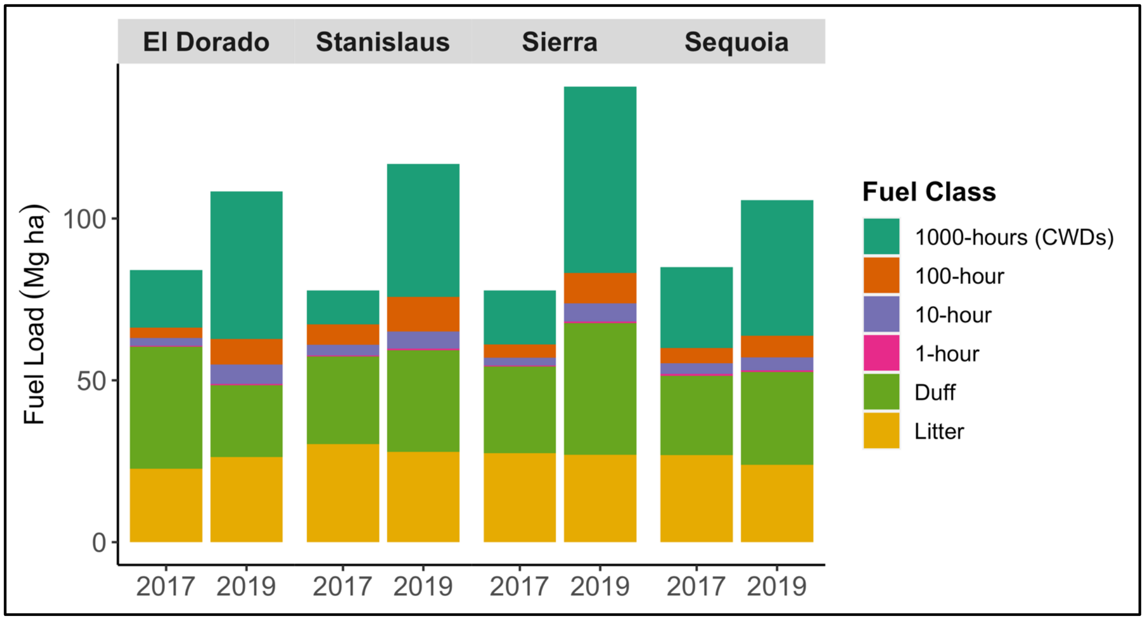

Figure 2. Ground and surface fuel loading (megatons per hectare) by national forest in 2017 and 2019 (*n* = 45/national forest).

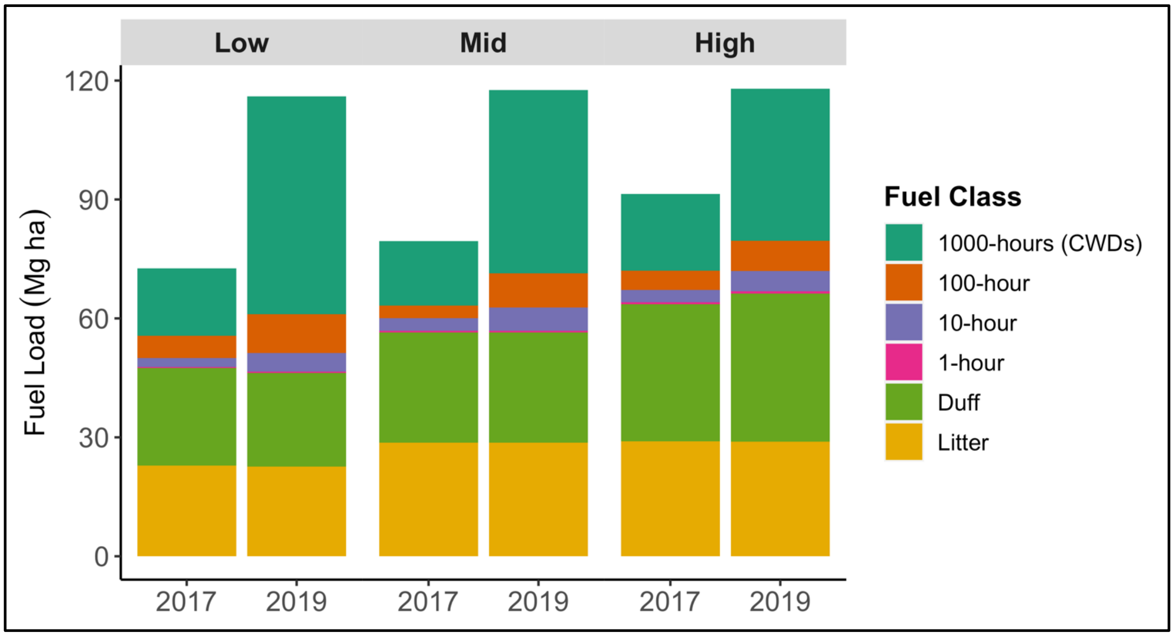

Figure 3. Ground and surface fuel loading (megatons per hectare) by elevation band in 2017 and 2019 (*n* = 60/elevation band). Low = 914–1218m on all national forests, except Sequoia (1219–1524 m); mid = 1219–1524 m, except Sequoia (1524–1829 m); high = 1524–1829 m, except Sequoia (1829–2134 m).

Keywords: bark beetles, *Dendroctonus brevicomis*, *Pinus ponderosa*, tree mortality

Acknowledgements: We thank numerous individuals for field assistance. This research was supported, in part, by grants from the Pacific Southwest Research Station Climate Change Competitive Grant Program and a UC Davis Graduate Research Award.

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Insect community responses to novel and co-evolved bark beetle pheromones: Predicting potential southern pine beetle associates in New England pine forests

Caroline Kanaskie[a], Matthew P. Ayres[b], and Jeff Garnas[a]
[a] Department of Natural Resources, University of New Hampshire, Durham, NH
[b] Department of Biological Sciences, Dartmouth College, Hanover, NH

Arthropod communities associated with the southern pine beetle (SPB, *Dendroctonus frontalis* Zimmermann) are highly studied in southern U.S. forests where the beetle is among the most important pests of pine (Berisford 2011, Reeve 2011). This well-characterized community includes natural enemies, co-occurring and potentially competing *Ips* and other *Dendroctonus* bark beetles, and a suite of opportunistic species. Changing climate, particularly warming winters, is facilitating northward range expansion for SPB (Ungerer et al. 1999, Trần et al. 2007). As its range expands, ecological theory suggests SPB will encounter novel communities (Gleason 1926, Davis and Shaw 2001, Davis et al. 2005). Community differences in the endemic and expanding range of SPB is a plausible driver of divergent behavior and population dynamics of the beetle. The SPB-associated insect community has only recently been described in detail in the expanding range as part of our research (Kanaskie et al. in prep). We continue to fill this gap by comparing insect attraction to three different semiochemical lures (Synergy Semiochemical): 1) SPB-focused (frontalin, alpha/beta pinene, with endo-brevicomin placed several meters away); 2) *Ips*-focused (ipsenol, ipsdienol, lanierone, alpha/beta pinene); 3) and a tree volatile control (alpha/beta pinene) in New England forests. We used each of these lures with Lindgren 12-funnel dry-cup traps in each of seven paired pitch and white pine sites (n=14) across Maine, New Hampshire, and Massachusetts. We carried out the first season of fieldwork associated with this project from May–September 2020; the second season is ongoing and will include May–November 2021. Preliminary results from a subset of sites suggest that in the 2020 field season, the *Ips* trap catch differed from the SPB and control trap catch (Figure 1). We see evidence that locality, seasonality, and minimum winter temperatures impact trap catch (Figure 1). We did not see differences between trap catch based on the dominant pine type (white or pitch pine) at each site.

We are currently sampling and identifying insects and will ultimately compare catch across sites, latitude, and dominant pine species. These comparisons will help predict species' responses to novel SPB pheromones in the beetle's expanding range. Building on our previous study of SPB gallery communities in pitch pine in NY, this work provides baseline knowledge of regional species pools and facilitates future study of the consequence of the arrival of a novel keystone species, including community-scale adaptation and/or shifts in composition, abundance, or behavior.

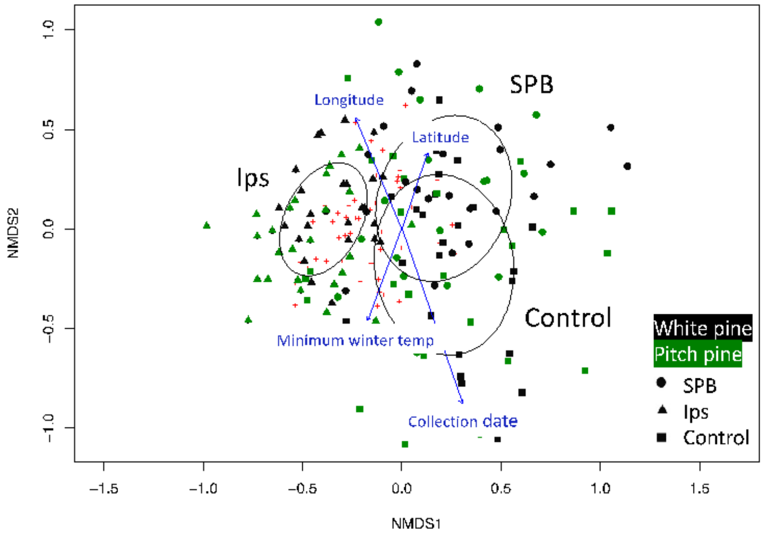

Figure 1. Non-metric multidimensional scaling (NMDS) ordination of trap catch from May–September 2020. Each point represents the insect community collected in one trap during one bi-weekly sampling event. Data was square-root transformed; distance calculated using Bray-Curtis distance measures. Stress = 0.184; two of three dimensions shown.

Keywords: *Dendroctonus frontalis*, pheromone baiting, community ecology

Acknowledgements: We thank our site partners, including USDA Forest Service, The Nature Conservancy, Town of Lancaster (MA), Town of Bourne (MA), the University of New Hampshire, New Hampshire Division of Forests and Lands, and Massachusetts Division of Fisheries and Wildlife. We also thank Dr. Claire Rutledge (Connecticut Agricultural Experiment Station) and Dr. Alicia Bray (Central Connecticut State University) for their collaboration that will ultimately add to the latitudinal gradient in this study. This work is funded by the UNH NRESS fund.

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POSTERS

Ecological role and forest regeneration impacts of the eastern spruce budworm in Minnesota and Isle Royale

Jessica M. Rootes[a] and Brian H. Aukema[a]
[a] University of Minnesota

Isle Royale National Park, located off the northeastern shore of Minnesota, consists of more than 450 islands that comprise approximately 130,000 acres of protected wilderness. This unique biosphere reserve is a haven for ungulates such as moose whose numbers have proliferated, resulting in undesirable levels of vegetation defoliation due to overbrowsing. This defoliation is further exacerbated by the native eastern spruce budworm (*Choristoneura fumiferana*). Though an ongoing 50+ year study analyzes moose and wolf predator-prey relationships, more studies regarding lower trophic levels and their impacts on the island's balsam-fir forests are needed. These studies will help to fill knowledge gaps regarding the ecological impact of efforts to relocate wolves to the island. Despite the eastern spruce budworm's potential large-scale impact and increasing populations, currently at a 20-year peak, this species has not yet been studied on Isle Royale. Outbreaks occur approximately every 35 years, last 10 years on average, and can result in 70% balsam fir and 40% white spruce mortality. My dissertation research will study the eastern spruce budworm's ecological role and effects on forest regeneration to evaluate restoration goals on Isle Royale. The project will consist of comparisons of population dynamics and related factors, such as weather conditions, parasitoids, and dispersal, between mainland Minnesota and Isle Royale.

Assessing the cold tolerance of elongate hemlock scale and its ability to establish in Minnesota

Marie Hallinen[a], Brian Aukema[a], Angie Ambourn[b], and Robert C. Venette[c]
[a] University of Minnesota
[b] Minnesota Department of Agriculture
[c] USDA Forest Service, NRS

The elongate hemlock scale (EHS), *Fiorinia externa* Ferris (Hemiptera: Diaspididae) is an insect from eastern Asia introduced to New York in the early 20th century. While it was historically found relatively close to its introduction point, it has greatly expanded its range since the 1970s and is now found in several New England and mid-Atlantic states and as far west as Michigan. In 2018, 2019, and 2020 EHS was found infesting wreaths, trees, and other greenery shipped into Minnesota to supplement Minnesota-grown Christmas trees. This armored scale has a wide host range and may feed and reproduce on many native local hosts, including firs and spruces, threatening forest health in addition to the Christmas tree industry in Minnesota. To assess the ability of EHS to survive winter temperatures in Minnesota we plan to measure the supercooling point, lower-lethal temperature, and lower lethal time of its overwintering stage. We will use these experiments to evaluate EHS's ability to potentially expand westward and overwinter in Minnesota.

Forest thinning improves native bee foraging habitat and is associated with increased bee abundances

Cora Davies[a] and Thomas Seth Davis[a]
[a] Colorado State University

In North American conifer forests, thinning operations are broadly implemented as a means of fire hazard mitigation, ecological restoration, and timber harvest. Effects of thinning on forest bee communities are poorly understood but could be important for conservation of biodiversity and ecosystem services. Here, we test the hypothesis that thinned forest stands have greater diversity of native bee species than non-treated forests. To address this, native bee assemblages were collected across the growing season and compared between ponderosa pine stands treated by mechanical thinning and non-treated stands. Associations between native bee communities and forest conditions were analyzed. Forest structure, floral resources, nesting habitat, and bee assemblages differed between treated and non-treated stands. Forest basal area at non-treated sites was on average 3.5 times greater than treated sites, and canopy openness was greater at treated sites. Fuel loads were similar between treated and non-treated sites. Floral resources were >2.5 times more abundant at treated sites; floral abundance was highest in June and decreased throughout the summer. Native bees were two times more abundant in treated stands. Our results suggest that (1) forest thinning has significant impacts on both floral resources and bee nesting habitats within 2-8 years post-treatment; (2) bee assemblages likely respond to this variation, and this difference is especially apparent later in the growing season. We conclude that forest thinning for ecological restoration in ponderosa pine habitats is likely to improve resources utilized by native bees and are associated with increased bee abundances in the wildland-urban interface.

Fear no weevil: understanding factors affecting hazelnut weevil infestation to safeguard a novel agroforestry crop

Pheylan A. Anderson[a], Hailey N. Shanovich[a], and Brian H. Aukema[a]
[a] University of Minnesota, Department of Entomology, Saint Paul, MN

Hybrid hazelnut crosses between the European hazelnut (*Corylus avellana*) and the American hazelnut (*Corylus americana*) are an emerging agroforestry crop in the Midwestern United States. European hazelnuts typically produce high yields, while American hazelnuts exhibit greater cold-hardiness and disease resistance. Hybrid hazelnuts are envisioned as a foundational species for making agroecosystems more sustainable: the perennial shrubs hold soil tightly, cycle nutrients, and do not require annual tillage inputs. However, little is known about how local insect communities will affect this novel crop. The hazelnut weevil, *Curculio obtusus*, is native to the US and typically infests native hazels in forests throughout the eastern United States. *Curculio obtusus* has been found to infest these new hybrid hazelnut cultivars across the Midwest, but little is known about what factors influence the severity or distribution of field infestations. We studied within-field distribution of *C. obtusus* by collecting a subsample of ten nuts from each of the 184 nut-bearing plants in an experimental hybrid hazelnut field in Rosemount, MN, and checked each for larvae or exit holes. Approximately 25% of the nuts

were infested with hazelnut weevil larvae, highlighting the need for understanding factors influencing the insect's infestation patterns. We analyzed spatial trends and whether factors such as plant genotype, historical rates of nitrogen application, plant height, and yield could predict weevil infestation using generalized linear mixed effect models.

Future directions of eastern larch beetle research in Minnesota

Emily R. Althoff[a] and Brian H. Aukema[a]
[a] University of Minnesota

Eastern larch or tamarack, *Larix larcina* (Du roi) K. Koch, ranges from Maine to Minnesota and Alaska in the United States, spanning almost 40,000 ha. of northern Minnesota. Within this range, tamaracks contribute to habitats for several birds and mammals and provide water filtration in northern wetlands, playing an essential role in these ecosystems. However, in the last 19 years, 40% of the state's 1.26 million acres of tamarack stands have been killed by eastern larch beetle, *Dendroctonus simplex* LeConte. Historically, ELB has only attacked tamarack stressed by windfall, fire, mechanical injury, defoliation, drought, or flooding. This trend has changed in recent years, as an outbreak of ELB has been ongoing in Minnesota since 2000. Previous studies have shown that warmer summer and/or extended growing seasons are facilitating bivoltine life cycles in a proportion of the population, demonstrating that some insects can reproduce without an obligate overwintering period. Information on the management of ELB is currently sparse as it has not been a widespread problem historically. In our future work, we plan to investigate stage-specific development and temperature triggers of a potential diapause in ELB, investigate potential semiochemical attractant or repellent lures for monitoring or management, and further advance understanding of associated natural enemies and competitors. Ultimately, we hope to assist in improving management practices and expand knowledge on how climate change influences insect development.

The efficacy of systemically injected Azadirachtin products at different doses and injection frequencies to control for the emerald ash borer (*Agrilus planipennis* Fairmaire, EAB)

Breanne Aflague[a], Rhoda deJonge[b], and Jeff Garnas[a]
[a] The University of New Hampshire
[b] Lallemand Plant Care

Injection of systemic insecticides is currently the most effective way to protect trees from the emerald ash borer, *Agrilus planipennis* Fairmaire (EAB). While previous academic studies have shown emamectin benzoate to be a highly effective active ingredient of these systemics, research on the use of azadirachtin-based insecticides in the control of EAB are limited. Azadirachtin is a botanically-derived active ingredient that is used when an effective low-toxic option for insect control is desired. Azadirachtin persists in trees for up to two years but can fluctuate seasonally; therefore, injection frequencies and doses are important factors to consider. We tested the efficacy of two azadirachtin-based systemics, Lalguard Aza (6% a.i. at both 4 ml and 6.5 ml/inch DBH dose rates) and TreeAzin (5% a.i. at a 12.5 ml/inch DBH dose) injected either annually or biennially, and compared them to untreated ash trees in a New Hampshire woodlot. Live larval densities where highly variable and differed moderately across treatments (including controls). Late instar larvae, however, were significantly reduced by the annual application of the Lalguard's low dose and at both injection frequencies by TreeAzin and Lalguard's high dose (Likelihood ratio chi- squared = 130.2; df = 6; $P < 0.001$). We also found an important effect of tree microenvironment (i.e., soil saturation) and old gallery density on larval densities and growth. These results suggest that both doses and injection frequencies of the Lalguard AZA and TreeAzin products are equivalently effective against EAB, though uptake can be inhibited in water-saturated microsites.

Elucidating stand-level characteristics critical for maintaining insect pollinators in working forests

Christine Favorito[a], James A. Martin[a], Angela Larsen-Gray[b], Daniel Greene[c], Christine Cairns Fortuin[a], Brittany F. Barnes[a], Elizabeth McCarty[a], and Kamal J.K. Gandhi[a]
[a] University of Georgia
[b] National Council for Air and Stream Improvement, Inc.
[c] Weyerhaeuser Company, Entoronmental Research South

Insect pollinators provide critical services to both people and forest ecosystems through crop and native plant pollination. Of the many insect pollinators present in forests, two of the most important indicators of ecosystem function and health are Hymenoptera (bees) and Diptera (flies). Unfortunately, bees are globally declining due to many factors including habitat loss and climate change, while the trend for many fly species is unknown. It is important to recognize the various and common aspects of forest structure and composition that best support these pollinators. Few studies have focused on pollinators in forests, and even less have focused on private, working forests, which make up 86% of forests in the southeastern U.S. We aim to compare populations and communities of wild bee and fly pollinators in various age classes of working forests, and to test the effects of stand-level structure and composition on bee and fly populations and communities. We are sampling bee and fly pollinators in 32 loblolly pine (*Pinus taeda*) stands with four age-classes in the Upper Coastal Plain region of Georgia using pan and blue vane traps in a randomized block design. We are measuring aspects of forest structure and composition (e.g., understory plants and coarse-woody debris) critical for these pollinators. We are currently identifying collected specimens to species. Results from this study will inform land managers of beneficial forest management practices for these pollinators that provide billions of dollars in pollination services annually.

Effect of a pine host volatile, 4-allylanisole, on southern pine beetle behavior

Sara K. O'Shields[a], Kamal J.K. Gandhi[a], Brian T. Sullivan[b], and Holly L. Munro[a]
[a] University of Georgia
[b] USDA-FS, Southern Research Station

Southern pine beetle, *Dendroctonus frontalis* Zimmerman (SPB) is a forest pest that has destroyed millions of acres of pines (*Pinus* spp.) in the eastern United States. SPB utilizes semiochemicals to initiate mass attacks and overcome host defenses. Likely because of SPB's close evolutionary history with host pines, specific host volatiles can enhance or inhibit SPB's response to its aggregation pheromone. One host volatile, 4-allylanisole (4 AA), was demonstrated in the 1990s to be an inhibitor of SPB aggregation, however, in recent field tests 4 AA strongly enhanced SPB attraction when paired with commercial lures. It is not yet understood why the results of the earlier and recent studies were different, and thus the biological significance of the contrasting studies is unknown. The goal of our current research is to explore this relationship and determine what factors influence SPB response to 4 AA. We will investigate how proximity of infested trees, trap-type, and presence of other semiochemicals (such as isomers of the SPB pheromone brevicomin and specific host odors) may affect SPB's responses to 4 AA.

Determining the impact of two biological control agents, *Laricobius nigrinus* and *Leucopis* spp. on *Adelges tsugae* populations and hemlock tree health in the eastern United States

Carrie E. Preston[a], Scott Salom[a], Albert Mayfield[b], Mark Whitmore[c], Jerome Grant[d], Tim Tomon[e], Biff Thompson[f], John Seiler[g], and Tim Kring[a]
[a] Virginia Tech, Department of Entomology, Blacksburg, VA
[b] USDA Forest Service, Southern Research Station, Ashville, NC
[c] Department of Natural Resources, Cornell University, Ithaca, NY
[d] University of Tennessee, Department of Entomology and Plant Pathology, Knoxville, TN
[e] Pennsylvania Department of Conservation and Natural Resources, Harrisburg, PA
[f] Maryland Department of Agriculture, Lonaconing, MD
[g] Virginia Tech, Department of Forest Resources and Environmental Conservation, Blacksburg, VA

Laricobius nigrinus, a biological control agent of *Adelges tsugae*, the hemlock woolly adelgid (HWA), has been able to establish populations at a high percentage of release sites throughout the eastern United States. While this specialist predator of HWA sistens nymphs and progrediens eggs impacts the sistens generation, progrediens populations appear to be able to rebound, likely due to the lack of specialist predators for this generation. Recently, *Leucopis argenticollis* and *Leucopis piniperda*, predators that are host specific to HWA in the Pacific Northwest, have been proposed as additional biological control agents that could aid in controlling HWA populations in the eastern US. *Leucopis* spp. have been observed feeding on both generations of HWA, therefore if *Leucopis* spp. were able to establish in areas where *L. nigrinus* is present, there could be constant predation pressure on HWA, potentially preventing HWA populations from rebounding. In 2019, four sites with established *L. nigrinus* populations and high HWA populations were selected for a study to determine the impact of *L. nigrinus* and

Leucopis spp. on HWA populations and to see if their predation would also have an effect on hemlock tree health. Mesh cages were applied on treatment branches with high HWA densities and to control branches, with low HWA densities, to compare the effect of both predators together and separately on the HWA population, to determine mesh cage effects, and to compare hemlock tree health measurements.

Efficacy of different packaging types and storage conditions for preventing active ingredient loss and cross-contamination of forest insect lures

William P. Shepherd[a] and Brian T. Sullivan[a]
[a] USDA Forest Service, Southern Research Station

Commercial devices for releasing forest insect attractants and repellants (used for monitoring pest populations and protecting trees) are commonly stored in a variety of packaging and conditions for extended periods. The packaging is permeable to varying degrees depending on its composition, thickness, closure type, storage temperature, and the chemical properties of the lure components. The packaging typically used by manufacturers, as well as practitioners who re-package the lures, consists of various plastics sometimes combined with other materials. Excessive permeability of the packaging may result in significant cross-contamination among different lures stored in proximity, which can alter the activity of the devices when deployed. Additionally, escape of chemicals from insufficient packaging may affect lure shelf-life and increase personnel exposure. We sent a survey to U.S. Forest Service, Forest Health Protection entomologists who regularly use semiochemical lures, asking them to describe semiochemicals used, target insects, release device construction, storage and transport practices, and general observations and concerns. Responses were used to help select relevant variables that we could test in experiments aimed at formulating recommendations regarding packaging of release devices. We measured rate of weight loss from lures and packaging both at room temperature and in consumer-grade freezers for (1) single vs. multiple layers of polyethylene bags and (2) various brands and thicknesses of Mylar bags, closed with zip lock-type seals or heat-sealed. The polyethylene bags were unable to prevent loss of volatiles at room temperature from any of the lures tested, although additional layers of bags delayed or slowed these losses.

Janet's looper northern jump: status of the range and host expansion of a native invasive defoliator in northern New Mexico

Jennifer Klutsch[a], Andy Graves[b], John Formby[c], Anna Schoettle, and Dan Ryerson[b]
[a] New Mexico Highlands University
[b] USDA Forest Service - R3 Forest Health Protection
[c] New Mexico EMNRD Forestry Division

Janet's looper (*Nepytia janetae*) recently jumped 200 miles north in NM defoliating 12,000 acres and expanding into Rocky Mountain bristlecone (*Pinus aristata*) and limber pine (*P. flexilis*). The addition of another invasive threat on top of white pine blister rust to high-elevation ecosystems can have major consequences for the maintenance of particularly Rocky

Mountain bristlecone. While Janet's looper can cause significant mortality in its native range, factors driving outbreaks are generally not known. Tree chemical defenses are associated with host suitability in other tree-defoliator systems and may be factors determining host suitability in the expanded host range of Janet's looper. We describe this recent expansion and propose a project to investigate site conditions and tree defenses in the expanded range of Janet's looper in the Sangre de Cristo Mountains, NM. Stands of Douglas-fir (*Pseudotsuga menziesii*), one of the historical hosts of Janet's looper along with 5-needle pines that have been defoliated and not defoliated will be sampled for needle defenses to identify factors associated with potential host suitability. Identifying the defenses that protect these high-elevation trees against this climate change-facilitated native invasive and site conditions are crucial to monitor the forest health in ecosystems already threatened by the invasive white pine blister rust.

Spatial and temporal heterogeneity after Hurricane Michael affects woodboring beetle populations and communities in southern U.S. pines

Chelsea N. Miller[a], Brittany F. Barnes[a], Sarah Kinz[a], James T. Vogt[b], and Kamal J. K. Gandhi[a]
[a] University of Georgia
[b] USDA Forest Service, Southern Research Station

Catastrophic wind disturbances including hurricanes, tornados, and derechos are a major cause of tree mortality in the southeastern U.S. Hurricane Michael, a Category 5 hurricane with wind speeds of 259 kph, made landfall in Florida on 10 October 2018, damaging ~1.13 million hectares of forest and over $1 billion in timber damage. Trees were uprooted, crowns, stems, and boles were snapped; stands were further subjected to prolonged flooding. Additional losses may occur from bark (Curculionidae) and woodboring (Buprestidae, Cerambycidae) beetles that infest wind-disturbed forests. Epidemic outbreaks following catastrophic disturbances can result in the spread of beetles from damaged to healthy trees, further exacerbating losses. Here, we characterize the responses of woodboring beetles to Hurricane Michael in Florida pine-dominated stands. We hypothesize that: 1) beetle populations will increase over the sampling period, and 2) that changes in populations will vary across stands with different levels of damage. To test these hypotheses, we sampled woodboring beetles using baited traps in 2019 and 2020 from 15 stands with low (<25% loss), moderate (25-75%), and high (>75%) damage (5 plots/category). Species thus far include at least 19 species such as *Monochamus* spp., *Acanthocinus* spp., *Curius dentatus*, *Xylotrechus sagittatus*, and *Buprestis lineata*. Preliminary results from 2019 indicate support for intermediate disturbance hypothesis, where highest numbers of woodboring beetles were trapped in moderately disturbed forests, particularly in September. Hence, moderately disturbed forests may need to be managed first to minimize future economic losses from beetle outbreaks following this and future wind disturbance events.

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PARTICIPANT LIST

Conference Registration for NAFIWC Virtual Conference
May 25 - 8, 2021

Breanne H. Aflague
Graduate Student
University of New Hampshire
Email: aflaguebreanne@gmail.com

Timothy Allen
Forest Pest Program Coordinator
Wisconsin DATCP
Email: timothy.allen@wisconsin.gov

Emily R. Althoff
Graduate Student
University of Minnesota
Email: altho065@umn.edu

Angie K. Ambourn
Supervisor
Agriculture Department Plant Protection Division
Email: angie.ambourn@state.mn.us

Pheylan A. Anderson
Research Technician
University of Minnesota, Department of Entomology
Email: and05170@umn.edu

Rachel A. Arango
Research Entomologist
USDA Forest Service
Email: rachel.arango@usda.gov

Christopher Asaro
FH Monitoring Program Manager
USDA Forest Service, FHP
Email: christopher.asaro@usda.gov

Jackson Audley
ORISE Postdoctoral Scholar
USDA Forest Service PSW Research Station
Email: jackson.audley@usda.gov

Brian H. Aukema
Professor of Forest Entomology
University of Minnesota
Email: bhaukema@umn.edu

Jodi Axelson
Research Leader, Silviculture
Resource Practices Branch – FLNRORD
Email: jodi.axelson@gov.bc.ca

Tara L. Bal
Assistant Professor
Michigan Technological University
Email: tlbal@mtu.edu

Brittany Barnes
Research Professional
University of Georgia
Email: barnes@uga.edu

Charles Barnes
Forest Pathologist
USDA Forest Service
Email: charles.barnes2@usda.gov

Chandler Barton
Forest Health Specialist
Arkansas Department of Agriculture
Email:
chandler.barton@agriculture.arkansas.gov

Amanda Beauregard
Biological Science Technician
USDA Forest Service
Email: amanda.beauregard@usda.gov

Barbara Bentz
Entomologist
Rocky Mountain Research Station
Email: barbara.bentz@usda.gov

Crystal Bishop
Graduate Student
Warnell School of Forestry and Natural Resources
Email: cb80216@uga.edu

Darren Blackford
Entomologist
USDA Forest Service, FHP
Email: darren.blackford@usda.gov

Jarrett Blair
PhD Student
University of British Columbia
Email: blair@zoology.ubc.ca

Katherine Bleiker
Research Scientist
Canadian Forest Service - Pacific Forestry Centre
Email: katherine.bleiker@nrcan-rncan.gc.ca

Alexandra Blevins
Forest Health Specialist
KY Division of Forestry
Email: alexandra.blevins@ky.gov

Michael Bohne
Forest Health Group Leader
USDA Forest Service
Email: michael.bohne@usda.gov

Pierluigi Bonello
Professor
Dept. of Plant Pathology, The Ohio State University
Email: bonello.2@osu.edu

Celia K. Boone
Research Forest Entomologist, Skeena Region
BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development
Email: celia.boone@gov.bc.ca

Ryan Bracewell
Entomologist
USDA Forest Service
Email: ryan.bracewell@usda.gov

Zachary Bragg
Graduate Research Assistant
University of Kentucky
Email: zachary.bragg@uky.edu

Sydney Brannoch
Entomologist
USDA Forest Service
Email: sydney.brannoch@usda.gov

Hannah J. Broadley
Biological Scientist
USDA APHIS PPQ S&T Forest Pest Methods Laboratory
Email: hannah.j.broadley@usda.gov

Harrison Brookes
Forest Health Program Manager
State of Wyoming
Email: harrison.brookes@wyo.gov

Beverly Bulaon
Entomologist
USDA Forest Service
Email: beverly.bulaon@usda.gov

Robert Cain
Entomologist
USDA Forest Service
Email: robert.cain@usda.gov

Wendy J. Caldwell
Executive Director
Monarch Joint Venture
Email: maczi001@umn.edu

Faith T. Campbell
President
Center for Invasive Species Prevention
Email: phytodoer@aol.com

Allan Carroll
Professor
University of British Columbia, Department of Forest and Conservation Sciences
Email: allan.carroll@ubc.ca

Val Cervenka
Forest Health Program Consultant
Minnesota Dept. of Natural Resources
Email: val.cervenka@state.mn.us

Lori Chamberlain
Forest Health Program Manager
Virginia Department of Forestry
Email: lori.chamberlin@dof.virginia.gov

Jennifer L. Chandler
Research Fellow
University of Massachusetts, Amherst
Email: chandler@umass.edu

Kevin Chase
Entomologist
Bartlett Tree Research Laboratory
Email: kchase@bartlett.com

Paul Cigan
Forest Health Specialist
Wisconsin DNR
Email: paul.cigan@wisconsin.gov

Stephen Clarke
Entomologist
USDA Forest Service, FHP
Email: stephen.clarke@usda.gov

Daniel Cluck
Entomologist
USDA Forest Service
Email: daniel.cluck@usda.gov

Tom Coleman
Entomologist/Slow The Spread
USDA Forest Service, FHP
Email: tom.coleman@usda.gov

Stephen Cook
Professor
University of Idaho
Email: stephenc@uidaho.edu

Janice Cooke
Professor
University of Alberta
Email: janice.cooke@ualberta.ca

Richard Cooksey
Director, Forest Health Protection
USDA Forest Service
Email: richard.cooksey@usda.gov

Robert L. Coulson
Professor
Knowledge Engineering Laboratory, Department of Entomology, Texas A&M University
Email: r-coulson@tamu.edu

Stephen Covell
Biological Scientist
USDA Forest Service
Email: stephen.covell@usda.gov

Ryan S. Crandall
Research Fellow
University of Massachusetts, Amherst
Email: rcrandall@umass.edu

Connor Crouch
Graduate Research Assistant
School of Forestry, Northern Arizona University
Email: connor.crouch@nau.edu

Molly Darr
Post-doctoral Fellow
Clemson University
Email: mndarr@clemson.edu

William C. Davidson
Forest Health Specialist
New Hampshire DNCR
Email: william.davidson@dncr.nh.gov

Gina A. Davis
Supervisory Entomologist
USDA Forest Service, FHP
Email: gina.davis@usda.gov

Ryan Davis
Entomologist
USDA Forest Service
Email: ryan.davis@usda.gov

John de Soto
University of Georgia
Email: jgd96746@uga.edu

Kenneth W. Dearborn
PhD Student
University of Toronto
Email: kenneth.w.dearborn@gmail.com

Katlin DeWitt
Forest Health Specialist
Virginia Department of Forestry
Email: katlin.mooneyham@dof.virginia.gov

Darci Dickinson
Forest Entomologist
USDA Oka-Wen NF
Email: darci.dickinson@usda.gov

Andrea Diss-Torrance
Invasive Insects Program Coordinator
Wisconsin DNR
Email: andrea.disstorrance@wisconsin.gov

Kevin Dodds
Entomologist
USDA Forest Service
Email: kevin.j.dodds@usda.gov

Robie Doerhoff
Forest Entomologist
Missouri Department of Conservation
Email: roberta.doerhoff@mdc.mo.gov

Jian J. Duan
Reasearch Entomologist
USDA Agricultural Research Service
Email: jian.duan@usda.gov

Rachel Dube
Forest Health Specialist
Minnesota Department of Natural Resources
Email: rachael.dube@state.mn.us

Deborah S. Page-Dumroese
Research Soil Scientist
USDA Forest Service RMRS
Email: debbie.dumroese@usda.gov

Tom Eager
Assistant Director
USDA Forest Service
Email: tom.eager@usda.gov

Tom Eckberg
Forest Health Program Manager
Idaho Department of Lands
Email: teckberg@idl.idaho.gov

Jeffrey M. Eikwort
Forest Entomologist
Florida Forest Service
Email: jeffrey.eickwort@fdacs.gov

Erica L. Eidson
Forest Health Specialist
Idaho Department of Lands
Email: eeidson@idl.idaho.gov

Joe Elkinton
Professor
University of Massachussetts
Email: elkinton@umass.edu

Patrick Engelken
Entomologist
USDA-FS State and Private Forestry
Email: patrick.engelken@usda.gov

Christine Favorito
Graduate Student: Masters
Universiy of Georgia
Email: christine.favorito@uga.edu

Christopher Ference
Plant Pathologist
USDA Forest Service, FHP
Email: christopher.ference@usda.gov

Christopher J. Fettig
Research Entomologist
USDA Forest Service, PSW Research Station
Email: christopher.fettig@usda.gov

Sima Feuer
Manitoba Government
Email: sima.feuer@gov.mb.ca

Robbie W. Flowers
Entomologist
USDA Forest Service
Email: robbie.flowers@usda.gov

Jeremiah R. Foley
Graduate Student
Virginia Tech
Email: folejr@vt.edu

John Formby
Forest Health Specialist/Entomologist
NM EMNRD Forestry Division
Email: john.formby@state.nm.us

Christine Fortuin
Post-doctoral Student
University of Georgia
Email: cfortuin@uga.edu

Michelle Frank
Pesticide & Invasive Plant Program Mgr
USDA Forest Service, FHP
Email: michelle.frank@usda.gov

Peter J. Gag
Forest Health Manager
North Dacota Forest Service
Email: peter.gag@ndsu.edu

Kamal Gandhi
Professor
University of Georgia
Email: kjgandhi@uga.edu

Jeff Garnas
Associate Professor
University of New Hampshire
Email: jeff.garnas@unh.edu

Holly Gatton
Lab Specialist
Virginia Tech
Email: hgatton@vt.edu

Monica Gaylord
Entomologist
USDA Forest Service - R3 Forest Health Protection
Email: monica.gaylord@usda.gov

Ben Gochnour
Graduate Student: PhD
University of Georgia
Email: bmg1110@gmail.com

Devin W. Goodsman
Research Scientist
Natural Resources Canada - Canadian Forest Service
Email devin.goodsman@canada.ca

Amanda Grady
Entomologist
USDA Forest Service - R3 Forest Health Protection
Email: amanda.grady@usda.gov

Elizabeth Graham
Entomologist
USDA Forest Service
Email: elizabeth.e.graham@usda.gov

Andrew Graves
Supervisory Entomologist
USDA Forest Service - R3 Forest Health Protection
Email: andrew.graves@usda.gov

Rebecca Gray
Forest Health Team Leader
Wisconsin DNR
Email: rebecca.gray@wisconsin.gov

Nicole Green
Entomologist
USDA Forest Service
Email: nicole.green@usda.gov

Laurel Haavik
Entomologist
USDA Forest Service
Email: laurel.haavik@usda.gov

Fred P. Hain
Director
Forest Restoration Alliance at NC State University
Email: fred_hain@ncsu.edu

Marie Hallinen
Forest Entomology Lab Manager
University of Minnesota
Email: halli154@umn.edu

Matt Hansen
Entomologist
Rocky Mountain Research Station
Email: earl.hansen@usda.gov

Sarah Hart
Colorado State University
Email: sarah.hart@colostate.edu

Jessica Hartshorn
Assistant Professor of Forest Health
Clemson University
Email: jhartsh@clemson.edu

Nathan P. Havill
Research Entomologist
USDA Forest Service, NRS
Email: nathan.p.havill@usda.gov

Ashley Hawkins
Forest Pathologist
USDA Forest Service
Email: ashley.hawkins@usda.gov

Chris Hayes
Entomologist
USDA Forest Service
Email: christopher.j.hayes@usda.gov

Alexandra G. Haynes
Graduate Research Assistant
University of Minnesota
Email: ahaynes@umn.edu

Andrea Hefty
Entomologist
USDA Forest Service
Email: andrea.hefty@usda.gov

Jeffrey Hicke
Professor
University of Idaho
Email: jhicke@uidaho.edu

Ashleigh Hillen
Graduate Student
Virginia Tech
Email: ashleighh@vt.edu

Mike Hillstrom
Forest Health Specialist
Wisconsin DNR
Email: michael.hillstrom@wisconsin.gov

Stacy HIshinuma
Entomologist
USDA Forest Service
Email: stacy.hishinuma@usda.gov

Richard W. Hofstetter
Professor
Northern Arizona University
Email: rich.hofstetter@nau.edu

Hannah Hollowell
Graduate Research Assistant
University of Kentucky
Email: hmho242@g.uky.edu

Crystal Homicz
PhD Student
University of California, Davis
Email: cshomicz@ucdavis.edu

Michael Howe
Postdoc
University of Wisconsin, Madison
Email: howe3@wisc.edu

Daegan Inward
Research Entomologist
Forest Research, Alice Holt, Alice Holt Lodge,
Wrecclesham, Farnham, Surrey, UK
Email: daegan.inward@forestresearch.gov.uk

Susannah T. Iott
Invasive Species Program Specialist
Michigan Department of Agriculture and
Rural Development
Email: iotts@michigan.gov

David Jenkins
Forest Health Program Manager
South Carolina
Email: djenkins@scfc.gov

Jay (Mike) Johnson

Todd T. Johnson
Postdoctoral Research Associate
University of New Hampshire, Department of Natural Resources and the Environment
Email: todd.johnson@unh.edu

Marcia Jones
Sales and Marketing Manager
Synergy Semiochemicals
Email: marcia@semiochemical.com

Michael Jones
Extension Forester
University of California Cooperative Extension
Email: mjones@ucanr.edu

Grayson B. Jordan
Graduate Student
Utah State University
Email: grayson.jordan@usu.edu

Carrie Jubb
Research Specialist
Virginia Tech
cjubb@vt.edu

Jackie Kaluzny
Manitoba Government
Email: jackie.kaluzny@gov.mb.ca

Caroline R. Kanaskie
PhD Student
University of New Hampshire - Department of Natural Resources & the Environment
Email: caroline.kanaskie@grad.unh.edu

Rachel H. Kappler
Forest Health Coordinator
Holden Forests & Gardens
Email: rkappler@holdenfg.org

Entomologist
USDA Forest Service
Email: jay.m.johnson@usda.gov

Steve Katovich
Entomologist
USDA Forest Service - State and Private Forestry
Email: steven.katovich@usda.gov

Melody A. Keena
Research Entomologist
USDA Forest Service, NRS
Email: melody.keena@usda.gov

Danielle Kelley
Forest Health Technician
USDA Forest Service
Email: danielle.kelley@usda.gov

Toriani Kent
Graduate Student
University of Idaho
Email: kent0183@vandals.uidaho.edu

Katherine Kitchens
PhD Student
University of British Columbia, Department of Forest and Conservation Sciences
Email: kate.kitchens@ubc.ca

Jennifer Klutsch
Assistant Professor
New Mexico Highlands University
Email: jklutsch@gmail.com

Rosalie Knipp
Forest Pest Program Coordinator
Missouri Department of Agriculture
Email: rosalee.knipp@mda.mo.gov

Devin Kreitman
Graduate Student
Rutgers University
Email: devin.kreitman@rutgers.edu

John Kyhl
Entomologist
USDA Forest Service
Email: john.f.kyhl@usda.gov

Beth R. Kyre
Research Assistant
University of Kentucky
Email: bethkyre@gmail.com

Sara Lalk
PhD Student
Clemson University
Email: slalk@clemson.edu

Julia Leone
PhD Candidate
University of Minnesota
Email: leone050@umn.edu

Andrew M. Liebhold
Research Entomologist
USDA Forest Service, NRS
Email: andrew.liebhold@usda.gov

Daniel L. Lindner
Research Plant Pathologist
USDA Forest Service
Email: daniel.l.lindner@usda.gov

Vanessa Lopez
Biological Scientist
USDA Forest Service
Email: vanessa.lopez@usda.gov

August C. Kramer
Graduate Student
University of Minnesota
Email: krame855@umn.edu

Gary M. Lovett
Senior Scientist
Cary Institute of Ecosystem Studies
Email: lovettg@caryinstitute.org

Laura Lowrey
Entomologist
USDA Forest Service
Email: laura.lowrey@usda.gov

Jorge E. Macias-Samano
Consultant
Forest Health and Semiochemicals
Email: jemaciass58@gmail.com

Martin MacKenzie
Forest Pathologist
USDA Forest Service
Email: martin.mackenzie@usda.gov

Lorraine E. Maclaughlin
Forest Entomologist
BC Forests, Lands and Natural Resource
Operations and Rural development
Email: lorraine.maclauchlan@gov.bc.ca

Chris MacQuarrie
Research Scientist – Forest Entomology
Canadian Forest Service – Great Lakes
Forestry Centre
Email: christian.macquarrie@canada.ca

Danielle Malesky
Forest Entomologist
USDA Forest Service, FHP
Email: danielle.malesky@usda.gov

Véronique Martel
Research Scientist
Canadian Forest Service – Laurentian Forestry Centre
Email: veronique.martel@canada.ca

Kyla Maslaniec
Manitoba Government
Email: kyla.maslaniec@gov.mb.ca

David Mausel
Regional Entomologist
USDA Forest Service
Email: david.mausel@usda.gov

Albert E. Mayfield
Research Entomologist
USDA Forest Service – Southern Research Station
Email: albert.e.mayfield@usda.gov

Joel McMillin
Zone Leader
USDA Forest Service - R3 Forest Health Protection
Email: joel.mcmillin@usda.gov

Angela Mech
Assistant Professor
University of Maine
Email: angela.mech@maine.edu

Arjan Meddens
Assistant Professor
Washington State University
Email: arjan.meddens@wsu.edu

Philip T. Marshall
Forest Health Specialist
Indiana Dept Natural Resources
Email: treedoctor49@gmail.com

Paul Merten
Entomologist
USDA Forest Service, FHP
Email: paul.r.merten@usda.gov

Chelsea Miller
Post-doctoral Student
University of Georgia
Email: chelsea.miller@uga.edu

Robert J. Miller
Invasive Species Prevention and Response Specialist
Michigan Department of Agriculture and Rural Development
Email: millerr35@michigan.gov

Jason Moan
Forest Health Program Manager
Alaska Division of Forestry
Email: jason.moan@alaska.gov

Jessie Moan
Entomologist
USDA Forest Service
Email: mary.moan@usda.govm

Randall Morin
Research Forester
USDA Forest Service
Email: randall.s.morin@usda.gov

Tim Morris
Graduate Student

Leif Mortenson
Biological Science Technician
USDA Forest Service
Email: leif.mortenson@usda.gov

Holly L. Munro
University of Georgia
Email: hmunro@uga.edu

Dorah M. Mwangola
Graduate Student
University of Minnesota
Email: mwang022@umn.edu

Andrea L. Myers
PhD Recipient
Michigan Technological University
Email: almyers@mtu.edu

Meghan Noseworthy
Research Manager
Natural Resources Canada - Canadian Forest Service
Email: meghan.noseworthy@canada.ca

John Nowak
Entomologist
USDA Forest Sevice, FHP
Email: john.t.nowak@usda.gov

Gabriela C. Nunez-Mir
Post-doctoral Fellow
Virginia Commonwealth University
Email: gcnunezmir@vcu.edu

Grace Nuttle
Masters Student
Clemson University
Email: gnuttle@g.clemson.edu

SUNY College of Environmental Science and Forestry
Email: tmorri04@esf.edu

William Oldland
Supervisory Entomologist
USDA Forest Service
Email: william.k.oldland@usda.gov

David G. Olson
Forest Health Specialist
Nebraska Forest Service
Email davidolson@unl.edu

Megan A. O'Neil
Insect and Disease Specialist
Minnesota Department of Natural Resources
Email: megan.oneil@state.mn.us

Katie O'Shields
Masters Student
University of Georgia
Email: sarakoshields@gmail.com

Daniel Ott
Entomologist
USDA Forest Service
Email: daniel.ott@usda.gov

Eric Otto
Forest Health Specialist
Minnesota Depatment of Natural Resources
Email: eric.otto@state.mn.us

Forest Palmer
Lab Manager
Clemson University
Email: jfpalme5@clemson.edu

Flavia Pampolini

Lucas Peng
Undergraduate Student
University of British Columbia, Department of Forest and Conservation Sciences
Email: lucaspeng0429@gmail.com

Kayla I. Perry
Postdoctoral Fellow
Ohio State University
Email: perry.1864@osu.edu

Toby R. Petrice
Research Entomologist
USDA Forest Service, NRS
Email: toby.petrice@usda.gov

Sarah Phillips
State Survey Coordinator
Missouri Department of Agriculture
Email: sarah.phipps@mda.mo.gov

Renee Pinski
Entomologist
Wisconsin Department of Agriculture, Trade and Consumer Protection
Email: renee.pinski@wisconsin.gov

Stanley Pokorny
PhD Candidate
University of British Columbia, Department of Forest and Conservation Sciences
Email: stanley.pokorny@ubc.ca

Therese M. Poland
Research Entomologist
USDA Forest Service, NRS
Email: therese.poland@usda.gov

Adrian Polini
Forestry Technician
Inland Empire Resource Conservation District
Email: apoloni@iercd.org

PhD Candidate
University of Kentucky
Email: fpa233@g.uky.edu

Emilee Poole
Graduate Research Assistant
University of Georgia
Email: emp66194@uga.edu

Carrie Preston
Graduate Student
Virginia Tech
Email: cep19@vt.edu

Robert Progar
National Program Lead, Entomology and Pathology Research
Insects
Email: robert.progar@usda.gov

Deepa Pureswaren
Research Scientist
Canadian Forest Service
Email: deepa.pureswaran@canada.ca

Nicole Quinn
Postdoctoral Research Assistant
USDA-ARS BIIRU and University of Massachusetts
Email: nfquinn@umass.edu

Robert Rabaglia
Entomologist
USDA Forest Service
Email: robert.rabaglia@usda.gov

Kenneth F. Raffa
Professor Emeritus
University of Wisconsin – Madison

Davide Rassati
Assistant Professor
University of Padova
Email: davide.rassati@unipd.it

CCAPS Reg
Email: ccapsreg@umn.edu

Jacques Régnière
Research Scientist
Canadian Forest Service
Email: jacques.regniere@canada.ca

Stacey Rice
Graduate Student
University of Idaho
Email: rice1381@vandals.uidaho.edu

Elizabeth Rideout
Graduate Research Assistant
Utah State University
Email: liz.rideout@usu.edu

Bill Riel
Research Officer
Canadian Forest Service
Email: wgriel@gmail.com

Lynne K. Rieske-Kinney
Professor, Forest Entomology
University of Kentucky
Email: irieske@uky.edu

Karen Ripley
Entomologist
USDA Forest Service
Email: karen.ripley@usda.gov

Email: kfraffa@wisc.edu

Iral Ragenovich
Entomologist
USDA Forest Service
Email: iral.ragenovich@usda.gov

Amanda Roe
Research Scientist
Canadian Forest Service, Great Lakes Forestry Centre
Email: amanda.roe@canada.ca

Jessica M. Rootes
Research Assistant
Natural Resources Science and Management
Email: roote017@umn.edu

Lucas Roscoe
Research Scientist
Natural Resources Canada, Canadian Forest Service, Atlantic Forestry Centre
Fredericton, New Brunswick
Email: lucas.roscoe@NRCan-RNCan.gc.ca

Fiona Ross
Pest Management Biologist
Manitoba Government
Email: fiona.ross@gov.mb.ca

Erica Rudolf
Graduate Research Assistant
Oregon State University
Email: rudolphe@oregonstate.edu

Daniel Ryerson
Natural Resource Specialist
USDA Forest Service - R3 Forest Health Protection
Email: daniel.ryerson@usda.gov

Scott Salom
Professor
Virginia Tech

William Shepherd
Entomologist
USDA Forest Service, Southern Research Station
Email: william.shepherd@usda.gov

David Showalter
Postdoctoral Scholar
Oregon State University
Email: showa028@umn.edu

Ben C. Smith
Research Scholar
Forest Restoration Alliance, North Carolina State University
Email: bcsmith6@ncsu.edu

Greg Smith
Forestry Officer
Canadian Forest Service
Email: greg.smith@canada.ca

Sandy Smith
Professor
Institute of Forestry & Conservation
John H Daniels Faculty of Architecture, Landscape & Design (Forestry)
University of Toronto
Email: s.smith.a@utotonto.ca

Sarah Smith
Curator
Michigan State University
Email: smith462@msu.edu

Sheri Smith
Regional Entomologist
USDA Forest Service
Email: sheri.smith2@usda.gov

Thomas F. Smith

Email: salom@vt.edu

Kishan Sambaraju
Research Scientist
Canadian Forest Service
Email: kishan.sambaraju@canada.ca

Ashley Schultz
Postdoctoral Fellow
Colorado State University
Email: anschulz7@gmail.com

Cynthia Snyder
Entomologist
USDA Forest Service
Email: cynthia.snyder@usda.gov

Steven Souder
Entomologist
USDA Forest Service - R3 Forest Health Protection
Email: steven.souder@usda.gov

Lia Spiegel
Entomologist
USDA Forest Service
Email: lia.spiegel@usda.gov

Seth Spinner
Graduate Masters Student
University of Georgia
Email: seth.spinner@uga.edu

Stephanie Stephens
Entomologist
USDA Forest Service
Email: stephanie.s.stephens@usda.gov

Marissa Streifel
Entomologist

Forest Pest Specialist
California Department of Forestry and Fire Protection
Email: tom.smith@fire.ca.gov

Richard Sniezko
Center Geneticist
USDA Forest Service
Email: richard.sniezko@usda.gov

Susan Tangora
Forest Health Manager
Michigan Department of Natural Resources
Email: tangoras@michigan.gov

Wayne E. Thogmartin
Research Ecologist
US Geological Survey
Email: wthogmartin@usgs.gov

Katheryn A. Thomas
Research Ecologist
US Geological Survey
Email: kathryn_a_thomas@usgs.gov

Clayton Traylor
Graduate Reseach Assistant
University of Georgia
Email: ct78244@uga.edu

Amy M. Throwbridge
Assistant Professor
University of Wisconsin – Madison
Email: amtrowbridge@wisc.edu

Michael Ulyshen
Research Entomologist
USDA Forest Service, Southern Research Station
Email: michael.d.ulyshen@usda.gov

James Vandygriff
Entomologist
USDA Forest Service, State and Private Forestry
Email: marissa.streifel@usda.gov

Brian Sullivan
Research Entomologist
USDA Forest Service, Southern Research Station
Email: brian.sullivan2@usda.gov

Jon D. Sweeney
Research Scientist
Canadian Forest Service
Email: jon.sweeney@canada.ca

Caterina Villari
Assistant Professor
University of Georgia
Email: cvillari@uga.edu

James T. Vogt
Biological Scientist
USDA Forest Service, Southern Research Station
Email: james.t.vogt@usda.gov

Kendra E. Wagner
Graduate Research Assistant
Mississippi State University
Email: kew570@msstate.edu

Mary C. Wallace
PhD Student
University of Kentucky
Email: mary.wallace@uky.edu

Samuel F. Ward
Assistant Professor
Mississippi State University
Email: sw2442@msstate.edu

Jen Weimer
Forest Health Specialist

Rocky Mountain Research Station
Email: james.vandygriff@usda.gov

Robert C. Venette
Research Biologist
USDA Forest Service
Email: robert.c.venette@usda.gov

James Wieferich
Forest Health Specialist
Michigan Department of Natural Resources
Email: wieferichj1@michigan.gov

Elizabeth Willhite
Entomologist
USDA Forest Service
Email: elizabeth.willhite@usda.gov

Linda Williams
Forest Health Specialist
Wisconsin Department of Natural Resources
Email: linda.williams@wisconsin.gov

Kenneth Z. Windstein
MSc. Student, Graduate Teaching Assistant,
Research Lab of Dr. Jeff Garnas
University of New Hampshire Dept. of
Natural Resources and the Environment
Email: kenneth.windstein@unh.edu

Jake Wittman
PhD Candidate
University of Minnesota
Email: wittm094@umn.edu

New Hampshire Department of Natural &
Cultural Resources
Email: jennifer.weimer@dncr.nh.gov

Debra Wertman
PhD Candidate
University of British Columbia, Department of
Forest and Conservation Sciences
Email: debra.wertman@ubc.ca

Caroline Whitehouse
Forest Health Specialist
Alberta Agriculture and Forestry
Email: caroline.whitehouse@gov.ab.ca

Simeon Wright
Forest Health Specialist
Michigan Department of Natural Resources
Email: wrights19@michigan.gov

Debra Wytrykush
Forest Entomologist
BC Ministry of Forests, Lands, Natural
Resource Operations and Rural Development
Email: debra.wytrykush@gov.bc.ca

Rosa Yoo
Regional Forester
New Jersey Forest Service
Email: rosa.yoo@dep.nj.gov

Christopher Ziadeh
Graduate Student
University of New Hampshire
Email: cz1008@wildcats.unh.edu

Appendix 1. Forest-insects species list

Insect Common Name	**Insect Scientific Name**	**Order: Family**
Goldspotted oak borer (GSOB)	*Agrilus auroguttatus* Schaeffer	Coleoptera: Buprestidae
Metallic wood borer	*Agrilus macer* LeConte	Coleoptera: Buprestidae
Emerald ash borer (EAB)	*Agrilus planipennis* Fairmaire	Coleoptera: Buprestidae
Lined buprestid	*Buprestis lineata* Fabricius	Coleoptera: Buprestidae
Longhorned beetle	*Curius dentatus* Newman	Coleoptera: Cerambycidae
Velvet longhorned beetle (VLB)	*Trichoferis campestris* (Faldermann)	Coleoptera: Cerambycidae
Arrowhead borer	*Xylotrechus sagittatus* (Germar)	Coleoptera: Cerambycidae
Longhorned beetle	*Monochamus* spp.	Coleoptera: Cerambycidae
Longhorned beetle	*Acanthocinus* spp.	Coleoptera: Cerambycidae
Exotic ambrosia beetle	*Anisandrus maiche* Stark	Coleoptera: Curculionidae
Hazelnut weevil	*Curculio obtusus* (Blanchard)	Coleoptera: Curculionidae
Western pine beetle (WPB)	*Dendroctonus brevicomis* LeConte	Coleoptera: Curculionidae
Southern pine beetle (SPB)	*Dendroctonus frontalis* Zimmermann	Coleoptera: Curculionidae
Mountain pine beetle (MPB)	*Dendroctonus ponderosae* Hopkins	Coleoptera: Curculionidae
Spruce beetle (SB)	*Dendroctonus rufipennis* (Kirby)	Coleoptera: Curculionidae
Eastern larch beetle (ELB)	*Dendroctonus simplex* LeConte	Coleoptera: Curculionidae
Western balsam bark beetle (WBBB)	*Dryocoetes confusus* Swaine	Coleoptera: Curculionidae
Polyphagous shot hole borer	*Euwallacea fornicatus* Eichhoff	Coleoptera: Curculionidae
Kuroshio shot hole borer	*Euwallacea kuroshio* Gomez and Hulcr	Coleoptera: Curculionidae
Red-haired pine bark beetle	*Hylurgus ligniperda* (Fabricius)	Coleoptera: Curculionidae
Small southern pine engraver	*Ips avulsus* (Eichhoff)	Coleoptera: Curculionidae
Six-spined *Ips* beetle	*Ips calligraphus* (Germar)	Coleoptera: Curculionidae
Five-spined engraver	*Ips grandicollis* (Eichhoff)	Coleoptera: Curculionidae
Pine engraver	*Ips pini* (Say)	Coleoptera: Curculionidae
European spruce bark beetle	*Ips typographus* Linnaeus	Coleoptera: Curculionidae
Walnut twig beetle	*Pityophthorus juglandis* Blackman	Coleoptera: Curculionidae
Redbay ambrosia beetle (RAB)	*Xyleborus glabratus* Eichhoff	Coleoptera: Curculionidae
Mediterranean oak borer (MOB)	*Xyleborus monographus* (Fabricius)	Coleoptera: Curculionidae
Balsam woolly adelgid (BWA)	*Adelges piceae* (Ratzeburg)	Hemiptera: Adelgidae
Hemlock woolly adelgid (HWA)	*Adelges tsugae* (Annand)	Hemiptera: Adelgidae
Pine adelgids	*Pineus* spp.	Hemiptera: Adelgidae
Asian woolly hackberry aphid	*Shivaphis celti* Das	Hemiptera: Aphididae
Elongate hemlock scale (EHS)	*Fiorinia externa* Ferris	Hemiptera: Diaspididae
Oystershell scale (OSS)	*Lepidosaphes ulmi* (Linneaus)	Hemiptera: Diaspididae
Beech scale	*Cryptococcus fagisuga* Lindinger	Hemiptera: Eriococcidae
Spotted lanternfly (SLF)	*Lycorma delicatula* (White)	Hemiptera: Fulgoridae
Redheaded pine sawfly	*Neodiprion lecontei* (Fitch)	Hymenoptera: Diprionidae

Woodwasp	*Sirex nigricornis* Fabricius	Hymenoptera: Siricidae
European woodwasp	*Sirex noctilio* Fabricius	Hymenoptera: Siricidae
Asian giant hornet	*Vespa manadarinia* Smith	Hymenoptera: Vespidae
Larch casebearer	*Coleophora laricella* (Hübner)	Lepidoptera: Coleophoridae
Browntail moth	*Euproctis chrysorrhoea* (Linnaeus)	Lepidoptera: Erebidae
Lymantria dispar asiatica	*Lymantria dispar asiatica* Vnukovskij	Lepidoptera: Erebidae
Lymantria dispar dispar	*Lymantria dispar dispar* Linnaeus	Lepidoptera: Erebidae
Janet's looper	*Nepytia janetae* Rindge	Lepidoptera: Geometridae
Bruce spanworm	*Operophtera bruceata* (Hulst)	Lepidoptera: Geometridae
Winter moth	*Operophtera brumata* Linneaus	Lepidoptera: Geometridae
Monarch butterfly	*Danaus plexippus* (Linnaeus)	Lepidoptera: Nymphalidae
Fruittree leafroller	*Archips argyrospila* (Walker)	Lepidoptera: Tortricidae
Baldcypress leafroller	*Archips goyerana* Kruse	Lepidoptera: Tortricidae
Eastern spruce budworm (ESBW)	*Choristoneura fumiferana* (Clemens)	Lepidoptera: Tortricidae
Western spruce budworm (WSBW)	*Choristoneura freemani* (Razowski)	Lepidoptera: Tortricidae