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Analysis

Compounding the Disturbance: Family Forest Owner Reactions to Invasive Forest Insects

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ABSTRACT

Invasive forest insect and pathogens (FIP) are having significant, direct, adverse impacts. Interactions between FIPs and forest owners have the potential to create ecosystem impacts that compound direct impacts. We assessed family forest owners' responses to numerous contingent behavior, FIP-outbreak scenarios in the northeastern USA based on FIP outbreak attributes. The survey was divided into four versions and each respondent was given four hypothetical scenarios and asked to gauge their certainty of each response. Sixty-eight percent of the hypothetical scenario responses (n = 2752) indicated an intent to harvest as a result of FIPs, and 49% indicated this intent with certainty. Eighty-four percent of respondents (n = 688) would consider harvesting for at least one of the four hypothetical scenarios presented, and 67% of respondents were certain of their intent to harvest for at least one of the four hypothetical scenarios. Harvest intention increased with greater FIP-related tree mortality and decreased with delayed total tree mortality. Owners with larger holdings, who had previously harvested forest products, and live on their forestland had greater intentions to harvest in response to FIPs. Results suggest that FIPs could transform the regional harvest regime with socio-ecological impacts that are distinct from those caused by FIPs or harvesting alone.

1. Introduction

Forest insects and pathogens (FIPs) have significant impacts on forests worldwide. In North America, the annual area affected by FIPs exceeds that of all wildfires (Hicke et al., 2012) and in the northeastern U.S., FIPs damaged over 8 million ha during the past 17 years (Kosiba et al., 2018). Climate change and global trade are increasing the spread and severity of FIPs (Ayres and Lombardero, 2000) and the number of invasive wood-boring insects in North America is projected to increase three-to-four-fold by 2050 (Leung et al., 2014). Thus, there is urgent need to understand the full impacts of FIPs. Many of the direct impacts have been well-studied; they include: selective mortality of tree species thereby altering forest structure and composition; disruption of carbon, water, and nutrient cycles; and reduction in ecosystem service provision including timber production, carbon storage, and habitat (e.g., see reviews by Lovett et al., 2016; Peltzer et al., 2010).

Less well-studied are the human-mediated indirect impacts of FIPs. Specifically, the presence of FIPs often instigates salvage logging, and even the threat of FIPs can trigger pre-emptive logging. From an ecosystem perspective there are arguments against salvage and pre-emptive logging (Lindenmayer et al., 2012); however, there are often valid motivations for such action, including disturbance regime and management objectives (D'Amato et al., 2018; Foster and Orwig, 2006). In some cases, the effects of logging may generate more profound ecosystem disruption and impacts on biodiversity than the FIP itself (Foster and Orwig, 2006; Thorn et al., 2018). Salvage logging is a common

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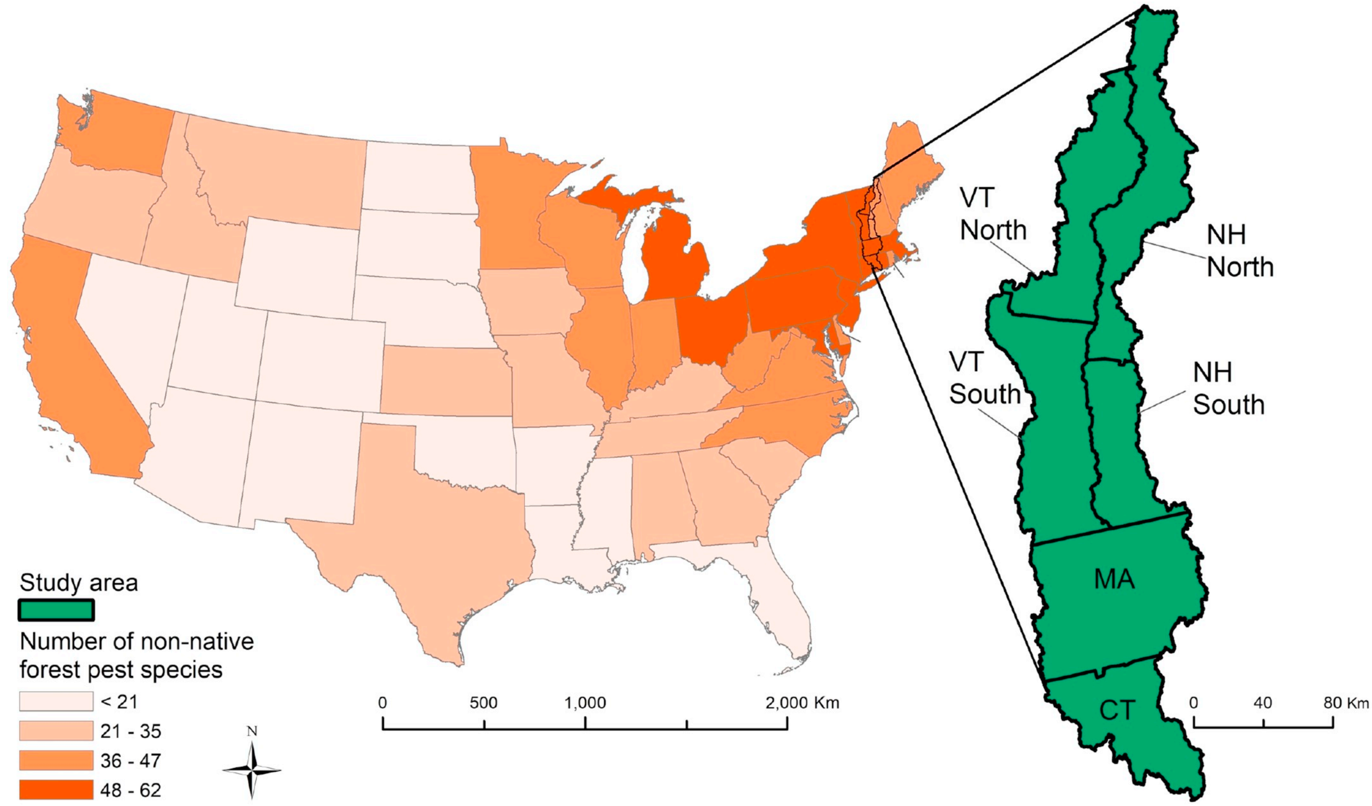

Fig. 1. The Connecticut River watershed study area and distribution of non-native forest insect pest species in the conterminous USA in 2015. (Adapted from: Cary Institute of Ecosystem Studies, 2019).

management response to forest disturbance with distinct ecological consequences that are increasingly recognized (Lindenmayer et al., 2012). Ecologically, the salvage response to FIPs can be considered a compounding disturbance that intensifies many aspects of the disturbance and often broadens the number of affected tree species (e.g., through harvest "by-catch" of more merchantable species to defray harvest costs). A full accounting of the direct and indirect impacts of FIPs mediated by the human response requires a coupled human and natural systems perspective and, specifically, a much better understanding of forest owner response.

Although many stakeholders influence the management response to FIPs, private forest owners are an essential group. Private forest owners control the plurality (58%) of forestland in the U.S.; approximately 36% is held by an estimated 11-million families, individuals, trusts, estates, and family partnerships, collectively referred to as family forest owners (FFOs) (Butler et al., 2016a). FFOs make independent forest management decisions as they see fit. In FFO-dominated landscapes, policymakers and conservationists are challenged by the "tyranny of small decisions," wherein the aggregation of many small independent decisions determine the regional-scale ecological outcomes without any explicit consideration of the broader context (Odum, 1982). Despite the widely acknowledged need for empirical studies of human behavior and decision-making regarding land management and conservation (Cowling, 2014; Field et al., 2017), few studies have investigated the management response to FIPs.

Studies of forest owner response to FIPs have focused on the southern pine beetle (SPB), which has infested much of the southeastern USA. These studies have characterized owners' willing to consider pre-emptive or salvage control measures and focused on approaches to motivate forest management and promote forest health (Mayfield III et al., 2006; Molnar et al., 2007). Here, harvesting was more likely among those having experience with forest management professionals, greater losses associated with SPB (Molnar et al., 2007) and larger landholdings (Mayfield III et al., 2006). SPB is an important species in the South (Schleeweis et al., 2013), but the number of different FIPs with unique, damaging attributes is growing worldwide (Liebhold et al., 2017). The SPB-focus of these studies precludes an understanding of other FIP attributes that are important to owners when considering management.

Here we investigate the FFO response to FIPs more generally, in the northeastern U.S., an ideal land system to study the human dimensions of FIP infestations. New England is among the most forested and populous regions of North America. Approximately 84% of forests are privately owned and 41% are owned by FFOs (Butler et al., 2016b). While wood products are not a dominant sector of the regional economy, partial forest harvesting is the dominant ecological disturbance, with attributes of the harvest regime (i.e., frequency and intensity of cutting) jointly controlled by social and biophysical factors (Thompson et al., 2017). FFOs in the region tend to own their land primarily for privacy and aesthetic reasons, but many harvest trees commercially (Butler et al., 2016a). Forest land management occurs infrequently and is triggered by poorly-understood, exogenous events (Kittredge, 2004; Markowski-Lindsay et al., 2016). Most owners do not have written forest management plans and have not received professional advice (Butler et al., 2016b). The Northeast also has the highest diversity of non-native FIPs in the USA (Fig. 1). The leading FIP species of concern include the hemlock woolly adelgid (*Adelges tsugae*), emerald ash borer (*Agrilus planipennis*), and gypsy moth (*Lymantria dispar*), which all have different host tree species with distinct ecological functions and services.

We hypothesize that a widespread FIP outbreak could serve to instigate harvest decisions by FFOs. To test our hypothesis, we surveyed FFOs to understand the circumstances under which FIP infestation would induce them to harvest. Our results suggest that future outbreaks of FIPs in the Northeast could alter the regional harvest regime, especially when FIPs cause high levels of tree mortality. This first step brings us toward a deeper understanding of whether FFO responses could result in regional-scale, possibly synchronized, socio-ecological consequences that exceed those of the FIP alone.

2. Materials and methods

2.1. Sample selection

We surveyed FFOs owning ≥4 ha within the 2.9 million ha Connecticut River watershed stratifying across six state/sub-state regions (Connecticut, Massachusetts, north and south New Hampshire, and north and south Vermont) (Fig. 1) and by parcel sizes of 4–19 ha and ≥20 ha, to ensure larger parcels were represented in the sample. We randomly selected FFOs within each stratum from property tax records. Prior to administration, the survey content and human subjects' protocol was reviewed and approved by the University's Institutional Review Board.

2.2. Survey design and administration

To assess likely FFO response to FIPs, we constructed a series of contingent behavior questions (Englin and Cameron, 1996) based on four key FIP attributes at varying levels: *(i)* arrival time, how virulent or damaging the FIP is, including *(ii)* tree mortality percentage and *(iii)* time until 100% tree mortality, and *(iv)* value of timber loss. We selected these attributes to reflect characteristics of the main FIPs in the northeast Lovett et al. (2006).

- Arrival time: while some areas have FIPs and others do not, we tested two FIP arrival times to get at this characteristic: current infestation and infestation in 5 years. Intention to harvest in response to the current infestation attribute reflects salvage logging, while intention to harvest due to an infestation likely to occur in 5 years could reflect either salvage or pre-emptive logging because the FFO was not asked to specify when harvest would take place.
- Tree mortality percentage: while some FIPs focus on one tree species (e.g., hemlock woolly adelgid) and others are indiscriminate or have multiple hosts (e.g., gypsy moth), we captured the range of potential FIP virulence with three mortality levels: killing 10%, 50%, and 90% of the trees.
- Time until 100% mortality of host trees is reached: the time it takes for FIPs to kill trees varies; as such, we tested two mortality rates: trees that would be killed within 5 or 15 years.
- Value of timber loss: differences in host specificity and associated tree value impacted by FIPs can result in differences in economic value losses, for example, the economic impacts of higher value ash losses likely differ from those of lower value hemlock. To test value of timber loss, we tested three values: timber reduction values of 10%, 50%, and 90%.

Each respondent was presented with four FIP infestation scenarios based on these generic FIP attributes and asked if they (or someone they hired) would harvest trees targeted by the FIP and how certain they were of their response for each scenario. The 36 possible scenarios were reduced to 16 using the standard fractional factorial design and then grouped into four survey versions – each version containing a distinct set of four scenarios reflecting plausible impacts based on the various FIPs in the region. For each hypothetical scenario, respondents were asked how certain they are about their answer to the question, using a 5-point Likert scale rating of certainty.

The survey asked respondents to provide information on numerous ownership and harvest-related characteristics. In addition to typical demographic characteristics, the survey asked about harvesting familiarity and ownership objectives (Table 1).

In 2017 we sent 2000 mail surveys to approximately 333 FFOs per strata, following methods described by Dillman et al. (2014). We obtained a 37% cooperation rate and based on follow-up telephone calls, detected no evidence of nonresponse biases. We imputed item nonresponse values using a random forests approach (sensu Stekhoven and Buhlmann, 2012).

2.3. Decision to harvest trees targeted by FIPs

A multilevel regression model (MLM) (Gelman and Hill, 2007) was used to account for the multiple scenario responses from each respondent. We established two separate MLMs of FIP-induced harvesting intention that incorporated respondent uncertainty: a base model relating the four attributes of the hypothetical FIP to harvest intention, and an expanded model supplementing the base model with owner-specific characteristics described in Table 1. We incorporated weights into the models to account for the stratified sample design. The weights, ω_s, were a function of the population size, N_s, and number of respondents, $n_{r,s}$, in each stratum, s, (i.e., $\omega_s = N_s / n_{r,s}$).

The base model described the probability of harvesting trees affected by the hypothetical FIP depending on the four FIP attributes varied in each contingent behavior question. We hypothesized that harvest intention would vary with FIP attributes. FIP attributes were coded as discrete categories, so that the model results would indicate the differences in harvest intent across the levels of the FIP attributes.

The expanded model included owner characteristics, and we hypothesized that, in addition to FIP attributes, harvest intentions would vary with characteristics commonly found in the FFO harvesting literature (see review by Silver et al., 2015) and the potential presence of a FIP already in a respondent's town. We tested demographics, including age, gender, education, income, absenteeism, land tenure, parcel size. Two measures covered harvesting familiarity, specifically whether they have cut commercially in the past and whether they have ever gotten advice about the care, management or protection of their woodland from a consulting forester or another professional. We explored several ownership objectives including timber production (i.e., owns for timber products, such as logs or pulpwood); land investment; consumption (i.e., owns for firewood, non-timber forest products or for hunting), protection (i.e., to enjoy beauty or scenery, to protect nature or biological diversity, to protect or improve wildlife habitat, or for privacy); and recreation (i.e., other than hunting). To characterize passive owners (sensu Silver et al., 2015), we also included whether the owner was likely to transfer their land in the near future. Finally, to examine whether the presence of a FIP in a respondent's town would induce harvest, we included whether two common FIPs had been detected in the respondent's town. (See Table 1).

We tested for multicollinearity among potential explanatory variables using Variance Inflation Factor (VIF) diagnostics; VIF tolerance levels below 0.4 are associated with high multicollinearity (Allison, 1999). The lowest level for variables in this analysis was 0.5.

Both models incorporated respondent uncertainty, which we measured by following the scenario questions with one that asked respondents to rate how certain they were of their answer, on a five-point Likert scale. We used the symmetrical uncertainty model as a guide by mapping responses to a numerical certainty scale (Loomis and Ekstrand, 1998). The numerical scaling projects a range of certainty onto the binary responses, with the lower end of the scale reflecting more certain negative responses, the middle scale the most uncertain responses, and the upper scale increasing certainty in positive responses (See Table 2).

For both models, we fit the data using ordinal logistic MLM (Greene, 2011) on the harvest intention coded to account for uncertainty. Ordinal models are based on latent variables governing respondent choices. We assume respondents make choices that increase their utility, and there is a continuous, unobservable variable that represents opinion level or utility association with their choice. While we do not directly observe respondents' utility for each scenario, we assume a transformation function (sensu Klosowski et al., 2001) that enables construction of the ordered model wherein we define unknown utility

Table 1
Survey data; model variables, definitions and coding.

Variable	Definition
FIP attributes	
Arrival time	Now (0), in five years (5)
Mortality percentage	Percent of trees killed: 10%, 50%, 90%
Time until full mortality is reached	Years to mortality: 5, 15
Value of timber loss	Percent of economic value loss: 10%, 50%, 90%
Expanded model characteristics	
Age	Years (continuous)
College degree	Has college degree: Yes (1), No (0)
Cut commercially in past	Yes (1), No/Don't know (0)
FIP found in town	Yes (1), No (0)
Gender (male)	Male (1), Female (0)
Income	Annual income $100,000 or more: Yes (1), No (0)
Lives on land	Lives within 1 mile of land: Yes (1), No (0)
Owns for consumption[a]	Very important/important (1), otherwise (0)
Owns for investment[a]	Very important/important (1), otherwise (0)
Owns for protection[a]	Very important/important (1), otherwise (0)
Owns for recreation[a]	Very important/important (1), otherwise (0)
Owns for timber production[a]	Very important/important (1), otherwise (0)
Parcel size	Size of woodland owned (hectares, logged)
Received professional advice[b]	Yes (1), No/Don't know (0)
Tenure	Number of years owning land (continuous)
Transfer of land likely in 5 years[c]	Extremely likely/likely (1), Otherwise (0)

[a] The survey asked respondents how important various reasons are for owning their land on a 5-point Likert scale of *Very important* to *Not important*. A respondent was coded as having the objective if they responded *Very important* or *Important* to the Likert scale for that question.

- Owns for timber production: Responded *Very important* or *Important* to “For timber products, such as logs or pulpwood”
- Owns for investment: Responded *Very important* or *Important* to “For land investment”
- Owns for consumption: Responded *Very important* or *Important* to any of the following: “For firewood”, “For nontimber forest products”, or “For hunting”
- Owns for protection: Responded *Very important* or *Important* to any of the following: “To enjoy beauty or scenery”, “To protect nature or biological diversity”, “To protect or improve wildlife habitat”, or “For privacy”
- Owns for recreation: Responded *Very important* or *Important* to “For recreation, other than hunting”

[b] The survey asked: “Have you ever gotten advice about the care, management or protection of your woodland from a consulting forester or another professional?”

[c] The survey asked respondents how likely it is they would sell or give away any of their woodland in the next 5 years on a 5-point Likert scale of *Extremely likely* to *Extremely unlikely*. If they answered *Extremely likely* or *Likely* they were coded as being likely.

Table 2
Scenario response coding for uncertainty (n = 2752).

Response	Certainty level	Ordinal logit coding	Response frequency (percent)
Yes	Very certain	5	492 (17.9%)
Yes	Certain	4	853 (31.0%)
Yes	Neutral, Uncertain, Very uncertain	3	532 (19.3%)
No	Neutral, Uncertain, Very uncertain	3	375 (13.6%)
No	Certain	2	340 (12.4%)
No	Very certain	1	160 (5.8%)

cutoffs delineating the five responses presented in Table 2 (sensu Greene, 2011). If a respondent's utility from a scenario is below the first cutoff, he or she chooses response 1; if utility is between the first and second cutoffs, the response is 2, etc. The first cutoff is normalized to zero, as is standard practice, thus the model estimates the four remaining cutoffs as presented in this table. We used the Stata15 *meologit* package using the *svyset* option to specify the survey design sampling units (i.e., respondents) and weights.

3. Results

Of the 2000 surveys, 688 respondents provided usable surveys. The models, accounting for correlation among the four scenario responses for each respondent, thus analyzed 2752 scenario responses. Nearly 50% of scenario responses were either certain or very certain about the intent to harvest in response to FIPs while nearly 20% of scenario responses were certain or very certain about the intent not to harvest (Table 2).

While we model responses, it is also informative to consider how *respondents* replied to scenarios. Cut intention for 63% of respondents varied with FIP attributes or reflected respondent uncertainty in their intention. Approximately 29% of respondents were certain about their intent to harvest under any of the four hypothetical scenarios given to them; and roughly 8% of respondents were certain about their intent *not* to harvest under any of the four hypothetical scenarios given to them. (See Table 3). Overall, 84% of respondents would consider harvesting for at least one of the four hypothetical scenarios presented (regardless of certainty), and when considering certainty, 66% of respondents were certain of their intent to harvest for at least one of the four hypothetical scenarios presented.

The majority of respondents were male, lived on their land, had a college degree, had experience cutting timber for commercial purposes, owned their land for the objective of protection, less often owned their land for investment or timber objectives, and were infrequently apt to sell or give away their land in the next 5 years (Fig. 2). Roughly half of respondents owned their land for consumptive or recreation objectives, and have received professional advice on the care, management or

Table 3
Cut intention by respondent (n = 688).

Response	Response frequency (percent)
Respondent would cut under every scenario and is *Very certain* or *Certain* about each of these responses	196 (28.5%)
Respondent cut intention and/or certainty varies across scenarios	435 (63.2%)[a]
Respondent would not cut under every scenario and is *Very certain* or *Certain* about each of these responses	57 (8.3%)

[a] Of these 435 respondents, 261 respondents (38% of the respondent sample) were certain about their intent to cut for at least one of the four scenarios presented to them; excluding certainty, 381 respondents (55% of the respondent sample) intended to cut for at least one of the four scenarios presented to them.

protection of their land. While the majority earned less than $100,000 per year, nearly 44% earned more than this. Nearly 45% lived in a town where one of the two leading FIP species of concern had already been detected. Respondents, on average, own 44 ha of wooded land, have owned their land for nearly 25 years, and are nearly 65 years of age (Fig. 2).

3.1. Models

FIP attribute coefficients and significance levels in the base and expanded models were nearly identical. Individually, both had significant F-statistics and the adjusted Wald test indicates significance (Table 4).

The odds ratios indicate how the FIP attribute levels influence the harvesting intent likelihood. Respondents are more likely to intend to harvest when FIPs kill a greater proportion of their trees (i.e., greater mortality effect; Fig. 3). A 50% mortality effect increases the odds of harvest intention by a factor of 2.8 over a 10% mortality effect, whereas a 90% mortality effect increases the odds of harvest intention by 4.2 over a 10% mortality effect. Harvest intention is also positively related to large differences in tree value loss. While respondent harvest intention does not differ significantly between a tree loss value of 50% and 10%, the odds of harvest increase by 1.6 with 90% value losses over 10% losses. Respondents are less likely to intend to cut the longer it takes for the FIP to kill the trees: increasing the time it takes for a FIP to kill all trees from 5 to 15 years decreases the odds of harvest intention by 0.73. Arrival time had no effect on intention to cut in this model. (See Fig. 3; Table 4).

Owner characteristics with the highest likelihood of harvest intention include: owning for timber and consumption, having past commercial harvests, and living on the land that they manage. Having these characteristics (versus not) increases the odds of harvest intention by more than a factor of 2. Two continuous factors influence FIP-induced harvest intention at lower significance levels: age and parcel size. Older respondents were less likely to cut; every 10 additional years in age decreases the odds of harvest intention to 0.8. Those owning more land are more likely to cut. Every 4 ha increase in land ownership raises the odds of harvest intentions by 1.5 (Fig. 3). The direction of these results is consistent with prior FFO harvesting studies (e.g., Aguilar et al., 2017; Silver et al., 2015).

4. Discussion

The majority of FFOs we surveyed indicated that their intent to harvest varied with FIP attributes. Similar to a southern USA study (Molnar et al., 2007), we found FIP mortality effects influenced harvest intention, and this influence was greatest of all attributes. The higher the percent of trees killed by the FIP, the greater the likelihood of harvest. While the timing of FIP arrival did not matter to respondents in their intent to harvest, a delay in the time for all trees to die decreased

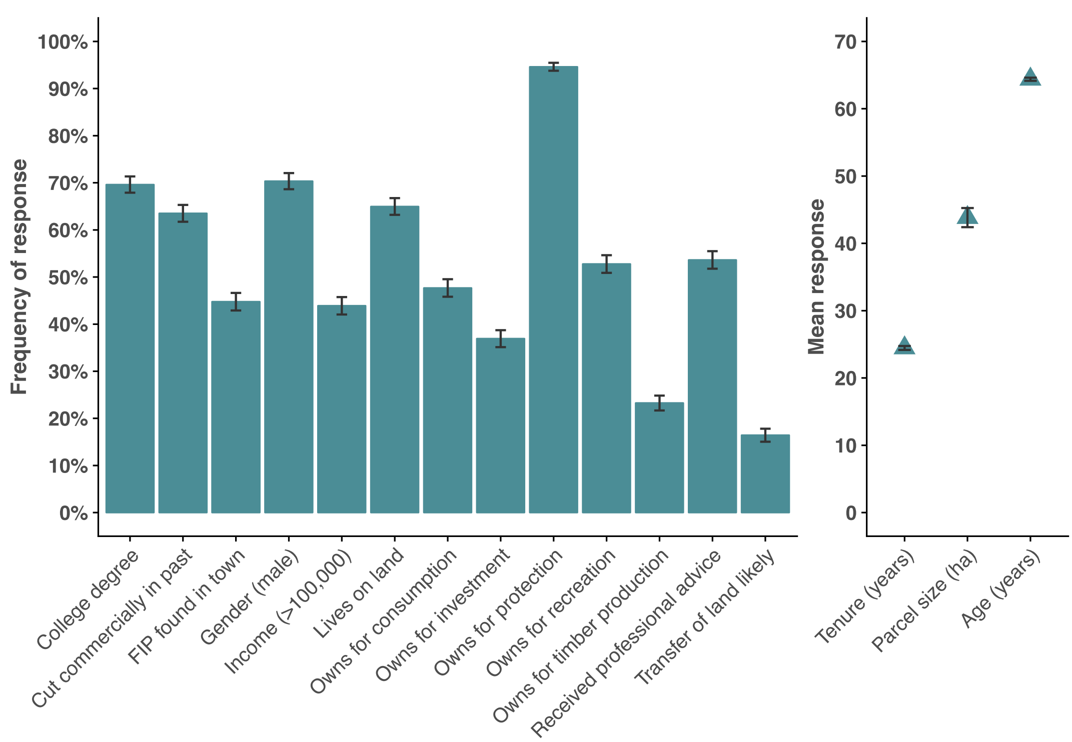

Fig. 2. Family forest owner characteristics frequency/means and 95% confidence intervals. The left panel shows discrete owner characteristic frequencies while the right shows continuous owner characteristic means.

Table 4
FIP attribute model comparison results for base and expanded models.

Independent variable	Base model[a]		Expanded model[a]	
	Coefficient	Odds ratio	Coefficient	Odds ratio
Arrival time 5 yrs (vs. now)	0.10	1.10	0.09	1.10
Mortality 50% (vs. 10%)	1.03†††	2.80†††	1.03†††	2.79†††
Mortality 90% (vs. 10%)	1.44†††	4.23†††	1.44†††	4.21†††
Time to 100% tree mortality 15 yrs (vs. 5)	−0.31††	0.73††	−0.31††	0.73††
Value of timber loss 50% (vs. 10%)	0.26	1.29	0.26	1.29
Value of timber loss 90% (vs. 10%)	0.47*	1.60*	0.47*	1.60*
Age			−0.02*	0.98*
College degree			−0.10	0.90
Cut commercially in past			0.76†	2.14†
FIP found in town			−0.23	0.79
Gender (male)			0.01	1.01
Income			0.33	1.39
Lives on land			0.71†	2.04†
Owns for consumption			0.89††	2.43††
Owns for investment			0.48	1.61
Owns for protection			0.12	1.13
Owns for recreation			0.08	1.08
Owns for timber production			1.05††	2.86††
Parcel size (ln(hectares))			0.29*	1.34*
Received professional advice			0.47	1.60
Tenure			0.004	1.00
Transfer of land likely			0.30	1.35
Cutoff 1	−4.47		−2.97	
Cutoff 2	−1.84		−0.34	
Cutoff 3	1.19		2.69	
Cutoff 4	4.60		6.11	
Var (constant)	10.37		8.77	

In both models, F-statistics are significant at $p < 0.00001$ (base: $F(6, 682) = 27.16$, expanded: $F(22, 666) = 11.2$; $n = 2752$). Adjusted Wald test for exclusion of additional independent variables in the expanded model is significant at: $F(16, 672) = 4.31$, Prob > F = 0.0000.

[a] *p*-value: ≤0.1% = †††, ≤1% = ††, ≤5% = †, ≤10% = *.

harvest intention. FIP arrival timing did not impact intent to harvest. Similarly, the value of timber lost did not greatly impact harvest intention confirming prior findings of how timber value does not motivate harvesting in the region (Kittredge and Thompson, 2016).

If these harvest intentions are borne out, there are likely to be regional-scale consequences of FIP infestations brought on by FFO management decisions. The harvest intention estimates in the study area (i.e., 29% of FFOs intend to harvest under every scenario and an additional 55% of FFOs said they may cut for at least one of the four scenarios presented to them) exceed the USDA National Woodland Owner Survey's harvesting estimates of similar FFOs from the larger, four-state region (Butler and Miles, 2016). Approximately 20% of these FFOs indicated they said they plan to cut or remove trees for sale in the next five years and roughly 20% of these FFOs have cut or removed trees for sale in the past five years (Butler and Miles, 2016). Moreover, the consequences in terms of effects on commodity production, ecosystem services, and biodiversity protection would be altogether different from FIP infestations alone. The effects of salvage logging are ecologically distinct (Thorn et al., 2018) and FIP-induced salvage harvests have particularly compounding impacts because they often remove trees and tree species that were not affected by the initial disturbance. For example, harvesting hemlock in response to hemlock woolly adelgid (HWA) in Connecticut and Massachusetts in the 1990s resulted in simultaneous removal of white pine and other more valuable hardwood species. These actions created stand composition and ecosystem changes that exceeded those that occurred with HWA mortality alone (Foster and Orwig, 2006; Orwig et al., 2002). Notably, these actions decreased the value of timber stands, altered nitrogen cycling, and created conditions that greatly increased the presence of invasive species (Brooks, 2004; Foster and Orwig, 2006; Kizlinski et al., 2002). FIP infestations may also serve as a harvesting trigger. Forest management decisions are motivated by various reasons and are largely uncoordinated (Kittredge, 2004; Markowski-Lindsay et al., 2016); however, FIP infestations potentially offer a region-wide synchronizing event among some FFOs, particularly when mortality impacts are high.

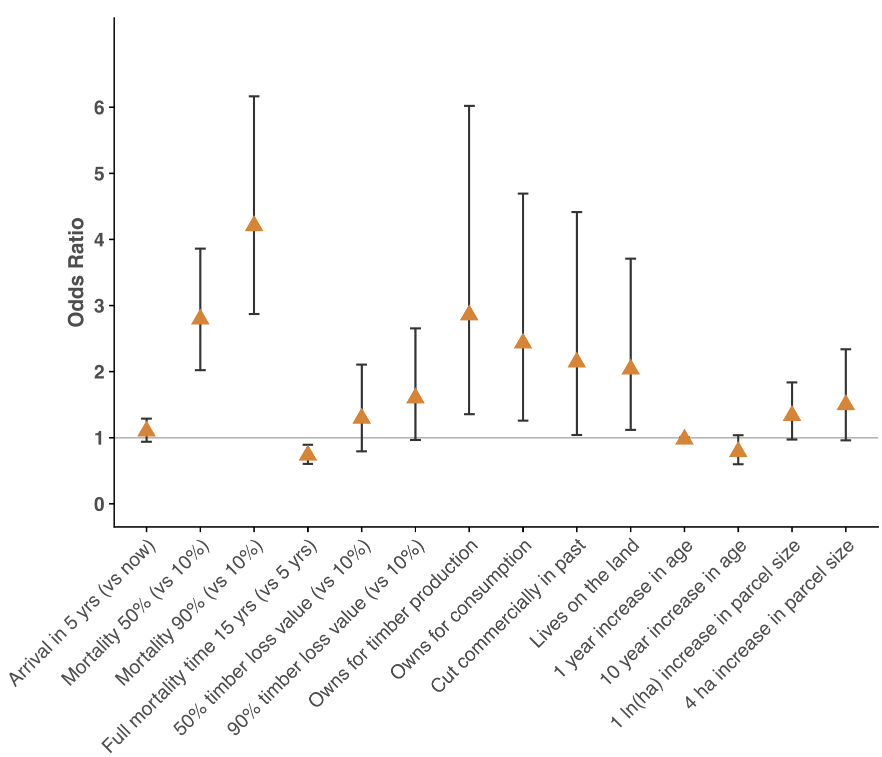

Fig. 3. Odds ratio results (with 95% confidence intervals) for FIP attributes (coded as discrete categories) and significant family forest owner characteristics ($p \leq 0.10$).

One such example of synchronous harvesting occurred during the 1990–1995 outbreak of jack pine budworm (*Choristoneura pinus pinus*) in northwestern Wisconsin (Radeloff et al., 2000). Certainly, a coordinated, synchronized harvesting event may be limited by poor wood markets or expense (Mayfield III et al., 2006), biophysical and social availability of wood from family forests (Butler et al., 2010), or other factors. Nonetheless, direct FIP ecosystem impacts may be exacerbated by such synchronicity, be they local or region-wide, creating a coupled natural- and human-disturbance system with even greater ecosystem repercussions than each one individually. FIP disturbances are growing with time (Ayres and Lombardero, 2000) and as the spread and – especially – severity increase with climate change, it is critical to understand the human response at national and global scales.

While it remains to be tested, our results suggest that FIP-induced harvest intention may be transferrable to other regions, especially those dominated by FFOs with similar characteristics. Here, FFOs with physically close ties to their land (i.e., experience with and goals of timber production, objectives of woodland resource consumption, and resident owners) had the greatest likelihood of harvesting, consistent with extant studies (Aguilar et al., 2017; Molnar et al., 2007; Silver et al., 2015). Across the U.S., 22% of ownerships own their land for timber, 29% have cut experience with commercial cutting, 44% for own for consumption purposes, and 63% of the ownerships were non-absentee (Butler et al., 2016b). Focusing specifically on the owners who own their land for timber (22% of all FFOs in the U.S.), our results suggest that FIP-induced harvest would be more likely on these roughly 94 million acres of forest, reflecting 37% of all FFO-owned land, than land owned by FFOs not having this ownership objectives. Focusing on resident FFOs (63% of all FFOs in the U.S.), our results suggest that FIP-induced harvest would be more likely on these roughly 148 million acres of forest, reflecting 56% of all FFO-owned land, then land owned by FFOs who do not live on their land.

Our next steps in assessing the complex feedbacks within this natural- and human-system will be to use these results in simulations designed to represent FFO behaviors as they are confronted with the presence or threat of infestation. These simulations will estimate regional-scale changes in forest structure, carbon and species composition as they are affected by FIP dynamics, climate change, and the land-use regimes articulated via FFO behavior models. The coupling between the behavioral model representing the human system and the forest simulation representing the natural system should be dynamic to capture the specific patterns that emerge from the complex feedbacks between the two. Additional research is also needed to understand how FIPs affect management and harvesting practices (sensu Molnar et al., 2007). Incorporating field and social science data into simulations can be used to better quantify the long-term and broad-scale impacts of FIPs on future forest conditions and to identify strategies that best conserve and sustain multiple ecosystem services and conservation values. Additional complexities to be pursued include better understanding of the marketplace system, including the impact flooded wood markets may have on decisions or the effect quarantines may have on timber transportation and the capability of loggers to respond to FFO harvest decisions.

Declaration of competing interest

None.

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References

Aguilar, F.X., Cai, Z., Butler, B., 2017. Proximal association of land management preferences: evidence from family forest owners. PLoS One 12, e0169667. https://doi.org/10.1371/journal.pone.0169667.

Allison, P.D., 1999. Logistic Regression Using the SAS System: Theory and Applications. SAS Institute, Cary, NC.

Ayres, M.P., Lombardero, M.J., 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci. Total Environ. 262, 263–286. https://doi.org/10.1016/S0048-9697(00)00528-3.

Brooks, R.T., 2004. Early regeneration following the presalvage cutting of hemlock from hemlock-dominated stands. North. J. Appl. For. 21, 12–18. https://doi.org/10.1093/njaf/21.1.12.

Butler, B.J., Miles, P.D., 2016. National Woodland Owner Survey Table Maker Ver 3.0 (Based on Data Collected from 2011 to 2013). Department of Agriculture, Forest Service, Northern Research Station, Amherst, MA: U.S. [Available only on internet. https://apps. fs.usda.gov/nwos/tablemaker.jsp.

Butler, B.J., Ma, Z., Kittredge, D.B., Catanzaro, P., 2010. Social versus biological availability of woody biomass in the northern United States. North. J. Appl. For. 27, 151–159.

Butler, B.J., Hewes, J.H., Dickinson, B.J., Andrejczyk, K., Butler, S.M., Markowski-Lindsay, M., 2016a. Family forest ownerships of the United States, 2013: findings from the USDA Forest Service's National Woodland Owner Survey. J. For. 114, 638–647. https://doi.org/10.5849/jof.15-099.

Butler, B.J., Hewes, J.H., Dickinson, B.J., Andrejczyk, K., Butler, S.M., Markowski-Lindsay, M., 2016b. USDA Forest Service National Woodland Owner Survey: National, Regional, and State Statistics for Family Forest and Woodland Ownerships with 10+ Acres, 2011–2013 (No. Res. Bull. NRS-99). U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Cary Institute of Ecosystem Studies and the Science Policy Exchange, 2019. Imported pests in the US. [WWW Document]. In: Map Import. Pests US, URL. https://www.caryinstitute.org/science-program/research-projects/tree-smart-trade (accessed 2.4.19).

Cowling, R.M., 2014. Let's get serious about human behavior and conservation: let's get serious about human behavior and conservation. Conserv. Lett. 7, 147–148. https://doi.org/10.1111/conl.12106.

D'Amato, A., Palik, B., Slesak, R., Edge, G., Matula, C., Bronson, D., 2018. Evaluating adaptive management options for black ash forests in the face of emerald ash borer invasion. Forests 9, 348. https://doi.org/10.3390/f9060348.

Dillman, D.A., Smyth, J.D., Christian, L.M., 2014. Internet, Phone, Mail, and Mixed-Mode Surveys: The Tailored Design Method. John Wiley & Sons, Hoboken, NJ.

Englin, J., Cameron, T.A., 1996. Augmenting travel cost models with contingent behavior data. Environ. Resour. Econ. 7, 133–147.

Field, C.R., Dayer, A.A., Elphick, C.S., 2017. Landowner behavior can determine the success of conservation strategies for ecosystem migration under sea-level rise. Proc. Natl. Acad. Sci. 114, 9134–9139. https://doi.org/10.1073/pnas.1620319114.

Foster, D.R., Orwig, D.A., 2006. Preemptive and salvage harvesting of New England forests: when doing nothing is a viable alternative: salvage harvesting in New England. Conserv. Biol. 20, 959–970. https://doi.org/10.1111/j.1523-1739.2006.00495.x.

Gelman, A., Hill, J., 2007. Data Analysis Using Regression and Multilevel/Hierarchical Models, Analytical Methods for Social Research. Cambridge University Press, New York, NY.

Greene, W.H., 2011. Econometric Analysis, 7th ed. Prentice Hall, Upper Saddle River, NJ.

Hicke, J.A., Allen, C.D., Desai, A.R., Dietze, M.C., Hall, R.J., Ted Hogg, E.H., Kashian, D.M., Moore, D., Raffa, K.F., Sturrock, R.N., Vogelmann, J., 2012. Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Glob. Change Biol. 18, 7–34. https://doi.org/10.1111/j.1365-2486.2011.02543.x.

Kittredge, D.B., 2004. Extension/outreach implications for America's family forest owners. J. For. 102, 15–18.

Kittredge, D.B., Thompson, J.R., 2016. Timber harvesting behaviour in Massachusetts, USA: does price matter to private landowners? Small-Scale For 15, 93–108. https://doi.org/10.1007/s11842-015-9310-1.

Kizlinski, M.L., Orwig, D.A., Cobb, R.C., Foster, D.R., 2002. Direct and indirect ecosystem consequences of an invasive pest on forests dominated by eastern hemlock. J. Biogeogr. 29, 1489–1503. https://doi.org/10.1046/j.1365-2699.2002.00766.x.

Klosowski, R., Stevens, T., Kittredge, D., Dennis, D., 2001. Economic incentives for coordinated management of forest land: a case study of southern New England. For. Policy Econ. 2, 29–38. https://doi.org/10.1016/S1389-9341(00)00035-6.

Kosiba, A.M., Meigs, G.W., Duncan, J.A., Pontius, J.A., Keeton, W.S., Tait, E.R., 2018. Spatiotemporal patterns of forest damage and disturbance in the northeastern United States: 2000–2016. For. Ecol. Manag. 430, 94–104. https://doi.org/10.1016/j.foreco.2018.07.047.

Leung, B., Springborn, M.R., Turner, J.A., Brockerhoff, E.G., 2014. Pathway-level risk analysis: the net present value of an invasive species policy in the US. Front. Ecol. Environ. 12, 273–279. https://doi.org/10.1890/130311.

Liebhold, A.M., Brockerhoff, E.G., Kalisz, S., Nuñez, M.A., Wardle, D.A., Wingfield, M.J., 2017. Biological invasions in forest ecosystems. Biol. Invasions 19, 3437–3458. https://doi.org/10.1007/s10530-017-1458-5.

Lindenmayer, D.B., Burton, P.J., Franklin, J.F., 2012. Salvage Logging and its Ecological Consequences. Island Press, Washington, DC.

Loomis, J., Ekstrand, E., 1998. Alternative approaches for incorporating respondent uncertainty when estimating willingness to pay: the case of the Mexican spotted owl. Ecol. Econ. 27, 29–41. https://doi.org/10.1016/S0921-8009(97)00126-2.

Lovett, G.M., Canham, C.D., Arthur, M.A., Weathers, K.C., Fitzhugh, R.D., 2006. Forest ecosystem responses to exotic pests and pathogens in Eastern North America. BioScience 56, 395. https://doi.org/10.1641/0006-3568(2006)056[0395:FERTEP]2.0.CO;2.

Lovett, G.M., Weiss, M., Liebhold, A.M., Holmes, T.P., Leung, B., Lambert, K.F., Orwig, D.A., Campbell, F.T., Rosenthal, J., McCullough, D.G., Wildova, R., Ayres, M.P., Canham, C.D., Foster, D.R., LaDeau, S.L., Weldy, T., 2016. Nonnative forest insects and pathogens in the United States: impacts and policy options. Ecol. Appl. 26, 1437–1455. https://doi.org/10.1890/15-1176.

Markowski-Lindsay, M., Catanzaro, P., Milman, A., Kittredge, D., 2016. Understanding family Forest land future ownership and use: exploring conservation bequest motivations. Small-Scale For 15, 241–256. https://doi.org/10.1007/s11842-015-9320-z.

Mayfield III, A.E., Nowak, J., Moses, G.C., 2006. Southern pine beetle prevention in Florida: assessing, landowner awareness, attitudes, and actions. J. For. 104, 241–247.

Molnar, J.J., Schelhas, J., Holeski, C., 2007. Nonindustrial private forest landowners and the southern pine beetle: factors affecting monitoring, preventing, and controlling infestations. South. J. Appl. For. 31, 93–98. https://doi.org/10.1093/sjaf/31.2.93.

Odum, W.E., 1982. Environmental degradation and the tyranny of small decisions. BioScience 32, 728–729. https://doi.org/10.2307/1308718.

Orwig, D.A., Foster, D.R., Mausel, D.L., 2002. Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. J. Biogeogr. 29, 1475–1487.

Peltzer, D.A., Allen, R.B., Lovett, G.M., Whitehead, D., Wardle, D.A., 2010. Effects of biological invasions on forest carbon sequestration. Glob. Change Biol. 16, 732–746. https://doi.org/10.1111/j.1365-2486.2009.02038.x.

Radeloff, V.C., Mladenoff, D.J., Boyce, M.S., 2000. Effects of interacting disturbances on landscape patterns: budworm defoliation and salvage logging. Ecol. Appl. 10, 233–247. https://doi.org/10.1890/1051-0761(2000)010[0233:EOIDOL]2.0.CO;2.

Schleeweis, K., Goward, S.N., Huang, C., Masek, J.G., Moisen, G., Kennedy, R.E., Thomas, N.E., 2013. Regional dynamics of forest canopy change and underlying causal processes in the contiguous U.S.: forest disturbance regional dynamics. J. Geophys. Res. Biogeosci. 118, 1035–1053. https://doi.org/10.1002/jgrg.20076.

Silver, E.J., Leahy, J.E., Weiskittel, A.R., Noblet, C.L., Kittredge, D.B., 2015. An evidence-based review of timber harvesting behavior among private woodland owners. J. For. 113, 490–499. https://doi.org/10.5849/jof.14-089.

Stekhoven, D.J., Buhlmann, P., 2012. MissForest–non-parametric missing value imputation for mixed-type data. Bioinformatics 28, 112–118. https://doi.org/10.1093/bioinformatics/btr597.

Thompson, J.R., Canham, C.D., Morreale, L., Kittredge, D.B., Butler, B., 2017. Social and biophysical variation in regional timber harvest regimes. Ecol. Appl. 27, 942–955. https://doi.org/10.1002/eap.1497.

Thorn, S., Bässler, C., Brandl, R., Burton, P.J., Cahall, R., Campbell, J.L., Castro, J., Choi, C.-Y., Cobb, T., Donato, D.C., Durska, E., Fontaine, J.B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R.L., Lee, E.-J., Leverkus, A.B., Lindenmayer, D.B., Obrist, M.K., Rost, J., Seibold, S., Seidl, R., Thom, D., Waldron, K., Wermelinger, B., Winter, M.-B., Zmihorski, M., Müller, J., 2018. Impacts of salvage logging on biodiversity: a meta-analysis. J. Appl. Ecol. 55, 279–289. https://doi.org/10.1111/1365-2664.12945.