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IMPACTS OF ENVIRONMENTAL DISTURBANCES ON HOUSING PRICES:

A REVIEW OF THE HEDONIC PRICING LITERATURE

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Abstract

The global environment is susceptible to many types of change, including alterations to the world's climate. Climate change has been linked to a host of modifications to the natural environment, including the increasing frequency and severity of disturbances such as pest outbreaks, invasions by non-native species, and wildfire. These in turn pose substantial risks to human wellbeing and health. Estimates of the direct and indirect costs of these events are important prerequisites to well-rounded cost-benefit analyses of preventative or control measures, themselves essential components of appropriate education, policy and management responses. This review brings together the evidence with respect to the impacts of disturbances such as pests, invasive species and wildfire on residential property values as measured using the hedonic pricing method. It demonstrates that whilst most disturbances have the expected negative or an insignificant house price impact, in some cases disturbances can lead to housing price rise. The possible causes and implications of these unanticipated positive price responses are discussed. Broader consequences of all directions of price impact are also considered, in particular for the development and implementation of polices designed to prevent the occurrence or spread of disturbances, or at a minimum mitigate their negative effects.

Keywords: hedonic pricing, pests, invasive species, fire, climate change

IMPACTS OF ENVIRONMENTAL DISTURBANCES ON HOUSING PRICES: A REVIEW OF THE HEDONIC PRICING LITERATURE

1. INTRODUCTION

The global environment is currently experiencing change of many types, including to its biodiversity, climate, food systems, land use and land cover, levels of ozone and pollution, urbanisation, and water resources. These changes pose risks to human society in the realms of health and safety, food security, infrastructural integrity, and basic livelihood (Global Environmental Facility, 2015; U.S. Global Change Research Program, 2016).

Climate change, for example, has been linked to a host of modifications to the natural environment that have substantial implications for human wellbeing and health. The Intergovernmental Panel on Climate Change (IPPC) states with "high confidence" that "Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change" (2014, p. 4) and with "very high confidence" that "Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability" (2014, p. 6). IPCC further notes that the incidence of disturbances such as wildfires and floods is likely to increase in multiple regions over the coming decades (wildfires across North America, southern Europe (e.g., Lozano et al., 2016) and Australia; floods in low-lying coastal zones, small island developing states, and inland floodplains across the globe). Though wildfires and floods can be natural occurrences (and the former are recognised as essential to effective ecosystem functioning), human activity has exacerbated the negative impacts of these types of events on human health and safety, e.g., via historic fire suppression policies as well as amenity-based migration into areas on the wildland-urban interface and in attractive coastal settings (Champ, Donovan & Barth, 2009; Stetler, Venn & Calkin, 2010).

Another threat associated with climate change is non-native or invasive species. According to Van Der Wal et al. (2008, p. 1428), “Non-native invasive plants are a widely acknowledged threat to global biodiversity;” similarly, the spread of invasives has been described “as one of the major threats to aquatic ecosystems” (Hyytiäinen, Lehtiniemi, Niemi, & Tikka, 2013, p. 69). Though invasive spread can be attributed to a variety of causes, including commerce (e.g., aquaculture, and seafood, aquarium and plant trade), land-use change, and transportation (e.g., via shipping and outdoor recreation/tourism), changing climatic and associated environmental conditions are also direct and indirect causes of spread. Changing temperatures support different species, for example, as do variations in the presence of other plant and animal species due to disease and/or lack of predators (Molnar, Gamboa, Revenga, & Spalding, 2008).

The ramifications of climate and associated environmental change for society are complex and manifold, and the need to quantify these effects has been recognised. From a forestry perspective, for example, Holmes, Murphy, Bell and Royle (2010, p. 538) stress that “A full accounting of the current and imminent economic losses due to the full constellation of non-native forest pests is essential for the development of informed policy that can meaningfully address the economic and ecological threats imposed by these ongoing threats to forest health.” According to Hansen and Naughton (2013, p. 142), “How climatically induced changes to natural disturbance regimes will influence the provision of environmental amenities is a pressing and unanswered question in sustainability science.”

A complete accounting of the direct and indirect implications and accompanying costs of the changes and associated risks described above is hard to conceptualise. One domain in which the enumeration of these hazards is more feasible, however, is impacts on residential property values. Kovacs, Holmes, Englin and Alexander (2011, p. 467) noted that, “Many natural hazards (e.g. wildfires, floods, and invasive species) have long-lasting effects on property values.” They go on to stress the importance of monitoring the human response to changing resource conditions and assessing the economic costs of natural hazards in order to maximise government response in terms of education, policy and management.

It is possible to assess the impacts of events such as fire, flood, or invasion by non-native species on prices that buyers are willing to pay for a home using the well-established hedonic pricing method (HPM, Rosen, 1974). The HPM recognises that many goods and services are comprised of bundles of individual attributes, and that whilst only one overall price is paid for the item, each attribute is discretely valued by potential buyers, e.g., a car’s features include levels of safety and comfort, engine size, fuel economy, and colour. The HPM therefore deploys regression analysis using overall sales price as the dependent variable to obtain implicit prices for individual characteristics (entered as the independent variables). In the case of houses, these characteristics are typically grouped into sets relating to individual lots/structures (e.g., square footage, number of bedrooms), the neighbourhood (e.g., crime rate, school quality), accessibility and the environment (e.g., location relative to the nearest downtown, transportation hub, park, water feature, etc.), and time of sale. This approach can therefore capture the value of aesthetics ((un)pleasant views of different (dis)amenities) and proximity or access to various resources, events or occurrences, whether they be considered positives or negatives.

According to Savills (2016), the value of all developed real estate in the world (including retail, office, industrial, tourism, residential, and agricultural uses) equates to approximately US$217 trillion, of which 75% is accounted for by residential property (approximately 2.5 billion households with a median value of $43,000); this total property value is 2.7 times the size of global GDP. Estimates of the damages to property caused by recent and potential invasive species invasions and wildfires are similarly enormous, e.g., the fires that swept northern California in late 2017 were projected to cause up to $65 billion in property damage (Disis, 2017) and the somewhat outdated though still most cited estimate of the annual cost of invasive species to the US alone exceeds $120 billion (Pimental, Zuniga & Morrison, 2005).

The present review therefore aims to bring together the evidence to date on this topic. As such, it collates and summarises work focusing on the impacts of those environmental disturbances most likely to be exacerbated in frequency and/or severity by projected climate change, specifically pests and pathogens (native and invasive, terrestrial and aquatic) and fire. The effects of floods and flood risk were not included given the very recent publication of a review paper on that particular hazard (Beltran, Maddison & Elliott, 2018).

2. METHOD

Acquisition of relevant studies commenced with a search of the author's library databases (including EBSCO, ProQuest, and Web of Science) as well as Google Scholar and ResearchGate. The reference lists of relevant pieces were reviewed for additional items. The following sets of key words were employed in the initial search: 'hedonic,' 'property/house price' or 'property/house value,' and 'disturbance, 'hazard,' 'exotic,' 'invasive,' 'pest,' 'pathogen,' or 'fire.' A total of 20 papers were identified, 13 on pests/pathogens and 8 on fire (with 1 looking at both). The review is divided into two parts, the first focusing on the effects of native and non-native animal and plant species on surrounding property values, and the second on the effects of fire and fire risk.

3. PESTS AND PATHOGENS

3.1. Native Species Infestations

Two studies have assessed the effects of beetle outbreaks on surrounding property prices (Table 1). The first focused on mountain pine beetles (MPB, *Dendroctonus ponderosae*), a species that has severely damaged coniferous forests throughout the western US and Canada, reducing their aesthetic and recreation utility to residents and increasing the risk of wildfire. In Grand County, Colorado, the number of trees killed by MPB within a 0.1, 0.5, and 1.0km buffer of each sold property reduced values by $648, $43, and $17 per dead tree, respectively; the closer a damaged tree was to a property, the greater its impact on price (Price, McCollum & Berrens, 2010). Given that the average number of trees killed by MBP within each of those buffers was 4, 93, and 367, respectively, total reductions relative to the average priced property (nearly $430,000) totalled $2,592 (1% of price), $3,999 (9%) and $6,239 (15%).

In the case of the spruce bark beetle (*Dendroctonus rufipennis*) on the Kenai Peninsula of Alaska, however, the impacts of outbreaks within 0.1-0.5 km and 0.5-1.0km were found to have significant positive impacts on assessed values, effects that were magnified with time since the outbreak (Hansen & Naughton, 2013). The explanation suggested for this unexpected finding was the opening up of pleasant views following a disturbance (due to associated loss of trees), and the perception of a reduced risk of future wildfire post-outbreak. The authors therefore proposed that homeowners do consciously process the complexities of environmental disturbance and, in this case, that the benefits of enhanced environmental amenities associated with an outbreak outweighed the costs.

Table 1 about here

3.2. Invasive/Non-Native Species

The US National Invasive Species Information Center (USNISIC, 2018b) defines invasive species as “plants, animals, or pathogens that are non-native (or alien) to the ecosystem under consideration and whose introduction causes or is likely to cause harm.” Invasive species include plants, animals, and other organisms (e.g., microbes), and most introductions are caused by human actions, e.g., via transportation and trade (Holmes, Aukema, Von Holle, Liebhold & Sills, 2009). In this subsection studies of the impacts of invasive species, both terrestrial and aquatic, on residential property values are reviewed.

3.2.1. Terrestrial invasives. A pair of studies has investigated the implications of the hemlock woolly adelgid (*Adelges tsuga*), an exotic forest insect, for residential property values in New Jersey, USA. Both analyses established a statistically significant relationship between values and hemlock health; similarly, both indicated spillover impacts from hemlock degradation, i.e., the existence of negative effects not only on directly impacted parcels but also on neighbouring properties. The first study (Holmes, Murphy & Bell, 2006), established the significant positive impact (“special aesthetic appeal”) of healthy hemlocks and a consistently significant negative impact of moderate defoliation. Severe hemlock decline, however, had no significant effect in any models, and dead hemlock had a significant positive impact in one of four cases. The authors attributed this latter finding to increased light reaching the forest floor in severely declining and dead hemlock stands, stimulating the growth of other, typically hardwood, tree species. The second study (Holmes, Murphy, Bell & Royle, 2010, also reported in Huggett, Murphy & Holmes, 2008) employed two different specifications. The cross-section method (which assumed any price impact to be constant over time) assessed the impact of varying hemlock health, whereas the difference-in-difference model allowed for gradual reductions in forest health to have negligible impact on values until a ‘period of impact,’ the threshold at which values declined. Findings confirmed that (i) hemlock decline caused significant reductions in values for parcels home to hemlocks and for nearby parcels (the aforementioned spillover effect), and (ii) threshold levels, beyond which all hemlock, irrespective of health, imbued a negative effect on values, did exist. The average loss per impacted parcel ranged from 1.1% to 1.6% of selling price, and the total economic losses on properties sold during the study period ranged from $0.64 million to $2.1 million depending on the specification employed (the range indicating the importance of accounting for spillover effects).

Only one study appears to have assessed the impact of an invasive disease on plant species, namely Kovacs et al.’s (2011) analysis of the effects of “Sudden Oak Death” (*Phytophthora ramorum*), a non-indigenous forest pathogen, in Marin County, California. The presence of dying trees (i) in nearby oak woodlands, (ii) in large numbers in the surrounding neighbourhood, and (iii) on individual properties, were each related to value discounts, though their magnitude and duration varied as described in Table 2. These included “moderate, persistent property value discounts (3-6%) for homes located near infested oak woodlands subject to continuous post-invasion declines in forest health,” (p. 445) with the most dramatic declines (8-15%) observed for properties subject to dying oaks both within the residential neighbourhood and in nearby woodlands. The three studies of the effects of terrestrial invasives on house values are summarised in Table 2.

Table 2 about here

3.2.2. Aquatic invasives. The most analysed invasive in terms of impact on surrounding property values is water milfoil (*Myriophyllum*), a rapidly growing weed that clogs waterbodies (thereby causing dangerous conditions for boaters and swimmers) and reduces species diversity by crowding out natives. A single study also assessed the impact of Zebra mussels (*Dreissena polymorpha*), recognised as an invasive in North America (e.g., in the Great Lakes), Great Britain, Ireland, Italy, Spain, and Sweden. Zebra mussels cause a variety of problems for industry, individuals and local ecosystems, clogging pipes and intakes, wounding recreationalists who inadvertently tread on them, outcompeting native species for food, and suffocating native mussels and clams. However, their presence can also lead to improved water clarity, reduced loads of suspended pollutants, and an increase in game fish prevalence, all likely to be perceived as positives by nearby home owners. Indeed, Johnson and Meder (2013) indicated a 10% premium for properties located on a Zebra mussel-infested lake, even after the impact of milfoil had been accounted for.

In the earliest milfoil analysis identified, its presence in one of ten New Hampshire lakes resulted in three very different outcomes depending upon model specification and functional form employed: a sales price decline of (i) an insignificant amount, (ii) 21% and (iii) 43% (Halstead, Michaud, Hallas-Burt & Gibbs, 2003). The authors suggested inadequate specification of the milfoil variable and collinearity between independent variables as the most likely causes of this range. They recommended future studies incorporate more detailed measures of the extent of milfoil infestation, the timing and success of eradication attempts, and homeowner awareness of this problem.

In the second study, the price premium for a house on a Wisconsin lake free of milfoil ranged from $28,000 to $32,087, depending on model specification and relative to the average sales price of $268,035 (Horsch & Lewis, 2009). Invaded lakes experienced an average decrease of 13% in land value and 8% in total value (land plus improvements). Multiplication of the average marginal willingness to pay for a location on a milfoil-free lake by the average number of impacted properties per lake revealed an average cost of $187,600 per year per additional infested lake. The authors noted the more than 500 infested lakes in the state of Wisconsin, and that the total amount of funding dedicated to aquatic invasive species management across the state was at the time of writing approximately $4 million. Also in Wisconsin, Johnson and Meder (2013) found that when entered alone, the presence of milfoil had no significant price impact, whereas when entered simultaneously with a variable accounting for the presence of Zebra mussels, the effect of milfoil became significant (-5%). Olden and Tamayo (2014) demonstrated a more substantial negative impact in King County, Washington, where the presence of milfoil reduced sales prices by $94,385, or 19%, an aggregate average cost of $377,542 per year per additional lake invaded.

In the Adirondacks of New York, however, the presence of milfoil was insignificant in three of four models; it did have the expected significant negative impact in the fourth case, generating a decline in price of about 6% (Tuttle & Heintzelman, 2015). The authors attributed the lack of significance to lake size, i.e., the possibility that sold parcels were on larger lakes where the milfoil outbreak was not visible from sold homes. Similarly, the presence of milfoil was found to be negative and significant in three of six models on Lake Coeur d'Alene, northern Idaho, though was insignificant in three others (Liao, Wilhelm & Solomon, 2016). The decline found equated to $64,255 (about 13%) and the lack of significance was again attributed to properties on parts of the lake to which milfoil had not yet spread.

Zhang and Boyle's (2010) study was unique in its use of data indicating both total aquatic macrophyte coverage – and proportion milfoil cover – of the water surface in front of each sold house, a far finer approach than the binary (presence/absence) variables applied to entire lakes in prior studies. Though coefficients on the milfoil variable were insignificant in the various models presented, those on the variable representing total plant growth were significant, suggesting that values diminished by up to 16% for incremental increases in infestation. Specifically, while an increase in coverage from less than 1% to 1-20% generated a 0.3% sales price drop, and from 1-20% to 21-40% coverage a similarly small drop (of 0.9%), an increase from 61-80% to over 80% resulted in a 16.4% reduction. Remediation was valued more highly than infestation; a reduction in coverage from >80% to 61-80% produced a 19.7% price increase. Recognizing the limitations of sample size (65 sales), principal component analysis and all-possible-regressions procedures were employed.

Most recently, a duration model of land conversion has been combined with the more traditional hedonic approach to demonstrate the effect of milfoil invasion on the probability that undeveloped properties near lakes in the Twin Cities of Minnesota are developed into single-family houses (Goodenberger & Klaiber, 2016). As expected, parcels near invaded lakes were significantly (37%) less likely to be developed than those on non-invaded waterbodies. The studies reviewed in this subsection are summarised in Table 3.

Table 3 about here

4. FIRE

The earliest identified assessment of the impact of wildfire on property prices was commissioned by the Federal Emergency Management Agency's Office of Cerro Grande Fire Claims and conducted by Pricewaterhouse Coopers (2001). Results suggested a significant decline of 3-11% for homes in Los Alamos County that had not been damaged by the Cerro Grande Fire of May 2000. Loomis (2004) used a similar pre-post design to evaluate the effects of the Buffalo Creek, Colorado, fire of 1996 on prices in nearby Pine, finding a decline of 15-16%.

A more sophisticated analysis assessed the effects of repeated (versus single) fires on surrounding prices, finding that a second fire had a more substantial initial negative impact (averaging -23%) than the first (averaging -10%) in Los Angeles County, California (Mueller, Loomis & González-Cabán, 2009). This differential might reflect the assumption that a first fire is a one-off event, whereas a second is perceived as evidence of greater vulnerability to fire hazard. Further, this study investigated the impact of time passed since a fire; results showed that the first fire generated a sustained price reduction, whereas the initial drop after a second was followed by a price rise after 5-7 years, a time period that the authors noted is associated with regeneration of natural vegetation and the likelihood of a previous fire beginning to disappear from residents' memories.

In another effort to refine the earlier pre-post approach, Huggett, Murphy and Holmes (2008) employed a difference-in-differences technique which considered prices before and in five six-month periods during and after three large fires. They found that prices dropped 13-14% in the six months after these fires, but recovered within a year, and that whilst the effect of distance from a fire boundary was negative and significant before the fires (illustrating the amenity value of location proximate to the forest), and positive and significant in the six months after the fires, the effect was insignificant by year's end.

Stetler, Venn and Calkin (2010) were the first to focus on multiple wildfires, specifically 256 fires all greater than 10 acres in extent that burned over a period of 17 years in northwest Montana. These fires were described as having had “large, persistent and negative effects on property values” (p. 2241), including a 2.6% decline for properties with a view of a burned area, magnified by another 3.5% reduction in the case of large (>405 hectares) fires. Properties located within 5km (-13.7%) and 5-10km (-7.6%) from a fire also experienced significant declines. Comparison of property sales with and without a view of a burned area further suggested that “when burned areas are out of sight, wildfire risk appears to be out of mind” (p. 2241).

Similarly, Hansen and Naughton (2013) considered all 1,193 fires burning between 1990 and 2010 on Alaska’s Kenai Peninsula. Their most unexpected finding was the significant positive impact of large wildfires on assessed values (of nearly 19% for properties within 0.1km of such a fire). Small fires had the expected significant negative impact (of -5.5%) within the same distance. The authors provided two potential lines of explanation for the unanticipated positive effect. First, that major fires opened up desirable ocean and mountain views by removing portions of dense forest that previously blocked these vistas, and second, that after a large fire homeowners’ perceptions of risk of future major wildfire was reduced. Most recently, Rossi and Bryne (2016) found that the number of fires occurring within 1.75 miles of a property in the five years prior to its sale had no significant price impact. However, as the authors observed, the incorporation of all homes in the county under analysis, including those outside of the wildlife-urban interface (WUI) zone, might have altered the results (of the 5,000 sales analysed, 2,936 were outside of the WUI and the average number of fires across all sales was 0.12).

The hedonic method has also been applied to assess effects of publication of parcel-level fire risk on price (Donovan, Champ & Butry, 2007, also reported in Champ, Donovan & Barth, 2009). In 2000, the Colorado Springs Fire Department published wildfire risk ratings (classified as medium, high, very high, and extreme) for 35,000 properties within their jurisdiction. Though the exact algorithm used to calculate risk was not released, the four most influential variables in the calculation were: construction material, proximity to dangerous topography, surrounding vegetation density, and average slope around property. Using spatially explicit regression techniques, analysis showed that whilst risk ratings were positively related to price prior to release of these ratings, after publication their impact was insignificant. The authors interpreted this change in the significance of the risk rating variables to suggest that their availability increased awareness of wildfire risk, a proposition supported by the decreasing preference for wood siding and roofing, both of which had significant negative impacts on prices post-publication. In other words, publication of the risk ratings was associated with a shift in understanding of certain factors such as construction materials and the presence of vegetation nearby, from representing desirable amenities to posing potential hazards. The studies reviewed in this section are summarised in Table 4.

Table 4 about here

5. DISCUSSION AND IMPLICATIONS

With a few interesting exceptions, the studies reviewed demonstrated the mostly negative effects of pests and pathogens, invasive species, and wildfire, on residential property values. These findings are summarised before their implications are discussed.

In the case of native species infestations (beetle outbreaks), evidence was mixed; in one case, such an outbreak caused a decline in values, whereas in the other the effect on prices was significant and positive. While two studies are clearly not a sufficient number from which to draw generalizable conclusions, these opposing results do at a minimum suggest the importance of contextual details (such as the type, height and density of surrounding vegetation, and the nature of local topography), and the need to factor in variables such as immediate and longer-range views before and after outbreak events. Findings such as these clearly demonstrate that home-owners and -buyers consider both short and longer-term, and near and more distant, benefits and costs, and that they do go through a personal weighting or prioritization process.

The importance of these kinds of contextual details was similarly evidenced in one of three analyses that assessed impacts of terrestrial invasives on tree health. In that case it was found that while healthy hemlocks had a significant positive impact on prices, and the effect of moderately defoliated hemlocks was significant and negative, the effect of severely defoliated hemlocks was insignificant and that of dead hemlocks was insignificant or positive. In the other two cases, negative effects were most prevalent, of a magnitude ranging from 1% to 15% of value; variations in effect with extent of nearby damage were observed, with less severe losses exhibiting shorter periods of negative impact.

Results with respect to the aquatic invader milfoil are both more numerous and more consistent in their demonstration of negative impacts. Across the seven traditional hedonic studies reviewed, a significant decline in price in the presence of milfoil was observed in at least one model in six cases (with magnitudes ranging up to -20% to -40%); insignificant effects were seen in five cases and positive effects in none (some studies tested multiple specifications hence total observations exceed seven). The existence of both negative and insignificant effects illustrates the various roles of model specification, and variable measurement and collinearity, in determining outcomes, e.g., in one case while the amount of Eurasian watermilfoil cover was insignificant, total aquatic macrophyte cover was significant. The only study to assess the impact of zebra mussels found a significant positive effect, a problematic outcome in terms of being unlikely to encourage compliance with or support for what are typically inconvenient and/or expensive mitigation and control measures.

The seven studies that investigated the effects of previous fire(s) demonstrated negative effects in all but one case; these effects were in the order of up to 20% of value. One of the most recent, however, did again illustrate the complex nature of homeowners' reactions to what at first thought might be considered solely as substantial dangers, i.e., that homeowners do weigh the positive and negative effects of fire and are able to see beyond potential hazards if aesthetic improvements are also brought about.

All 20 studies reviewed were conducted in the USA. Given the increasing prevalence of natural disturbances across the globe, and the relatively widespread availability of the tools necessary to implement the hedonic technique, attention to this topic in other geographic areas would appear to be warranted. The consistent use of multiple listing service databases and accompanying software by real estate brokers in the US provides an easy way to access the necessary data in that country; lack of availability of and/or access to similar sales price and associated property data are quite possibly the hindering factors in other locations.

None of the studies reviewed assessed the time to sale of properties post-disturbance. In the most drastic cases, it could be that homes have become "unsellable," an impact which would not be captured in a traditional hedonic study. Similarly, no study calculated potential losses to the local property tax base of sales price reductions, or the associated knock-on effect on municipal spending levels (including the amounts available to treat, maintain or improve areas impacted by disturbance). Such knowledge of the fiscal risks associated with price and resulting tax base losses could be used to justify local spending on hazard reduction or treatment, at least up to the amount potentially to be lost. Goodenberger and Klaiber (2016) did, however, stress the public policy implications of the reduction in development potential associated with milfoil-invaded lakes, in terms of potential for increased development pressures on non-invaded water bodies and associated concerns regarding sprawl and congestion on and around unaffected resources.

Several increasingly prevalent invasives were conspicuous in their absence from the extant literature; no analyses were found of the effects of Japanese knotweed or Asian carp, for example. Japanese knotweed is a rapidly spreading invasive herbaceous perennial in the UK that can cause so much damage to structures and foundations that most mortgage companies will not consider lending on an impacted property without evidence of treatment that will eradicate the plant (Council of Mortgage Lenders 2018). The 16-page TA6 Seller's Property Information Form, completed by UK home sellers, now includes questions regarding the presence and any treatment of knotweed, in addition to those relating to disputes, alterations, insurance, flooding, and energy efficiency. Asian carp represent a great threat to the US due to their alteration of natural balances of plant, invertebrate, and fish species in the waters they invade; in addition, the tremendous jumping abilities of some species have caused serious injury to water-based recreationalists. Numerous Great Lakes states and the Province of Ontario have filed lawsuits in attempts to prevent the spread of Asian carp into the Great Lakes, suggesting that the implications for lakefront property could be anticipated to be tremendous.

Assessment of the impacts of natural disturbances are complicated by the inherent attractiveness of most of the resources related to which they occur. Whilst the growth of milfoil may be considered a disamenity by a homeowner, for example, location on a lake is typically considered a plus; likewise, though wildfire and beetle outbreaks may do harm to property and its prices, views of the vegetation that supports those disturbances is often a source of price premium. Simultaneous inclusion of variables designed to capture both the benefits and the risks associated with these kinds of locations, as per Stetler et al. (2010), is therefore critical. Similarly, since some disturbances are inter-related, i.e., have a tendency to co-occur, it is important to consider them concurrently. For example, as Price, McCollum and Berrens (2010) note, the increasing number and severity of beetle outbreaks can largely be attributed to fire suppression practices and drought, factors also directly related to wildfire risk (both of which are projected to increase in frequency and intensity under projected conditions of climate change).

As Huggett et al. (2008) explain, different kinds of disturbance do manifest themselves, spread and dissipate at different intensities and speeds, with varying implications in terms of reaction by the housing market. Similarly, impacts also vary spatially. While some disturbances (e.g., a major wildfire) affect entire housing markets, others have much smaller and localised effects which are more likely to generate spillover from impacted properties to those not directly disturbed (e.g., milfoil invasions on very large lakes). The evolution of the hedonic method to enable consideration of both temporal dynamics and spatial dependency enables these fine scale variations in impact to be more effectively modelled; consideration of these nuances should become the norm in future assessments.

Quantification of the price effects described above represents an important step towards the more comprehensive and more accurate accounting of both the benefits and costs associated with the types of environmental disturbance most likely to increase in frequency and severity as a result of projected climate change. Such enumeration is an essential prerequisite to the formulation of more informed decisions regarding management strategies including identification of the most appropriate land uses and treatment approaches. Such decision-making should involve all pertinent stakeholders, including policymakers at all relevant levels (local, regional, (inter)national), resource managers and regulators, landowners, neighbourhood associations, non-local users (e.g., recreation groups), and other concerned individuals/groups.

From a policy perspective, development of policies designed to internalise the negative externalities of disturbances such as pests, pathogens and fire first requires evaluation of trade-offs between the loss of economic well-being they cause, and the costs associated with those policies' design and implementation. For example, reliable estimates of damages including those relating to property values are an essential input into strategies that attempt to shift the burden of the economic impacts of invasive species from resource owners/managers and taxpayers onto those parties responsible for introducing and/or spreading said species; both the imposition of tariffs on certain products and the introduction of new processing standards have been proposed as potentially efficient means of internalizing the invasive-related economic spillovers associated with regional and (inter)national transportation and trade (e.g., Holmes et al. 2009, 2010). Design, implementation and enforcement of such penalties is especially complicated in cases when those most impacted by disturbances are least responsible for their occurrence. Milfoil, for example, is most commonly spread by non-resident boaters and migratory waterfowl. In the case of the former, the challenge is to build the predilection to voluntarily engage in behaviours that will minimise spread even when the negative effects of that spread are not necessarily even visible let alone material to one-time or occasional users.

In all cases, actions to halt or at least reduce the negative outcomes associated with the occurrence or spread of disturbances are unlikely to materialise as long as the perceived cost of prevention or mitigation exceeds the perceived benefits of such action. Education is a critical need in terms of illustrating risk and incentivising change in behaviour including the willingness to support the cost of control or prevention measures (Andreu, Vilà, & Hulme, 2009; García-Llorente, Martín-López, Nunes, González, Alcorlo, & Montes, 2011). Numerous case studies have demonstrated the impactful role that schemes such as the National Fire Protection Association's Firewise program and the Stop Aquatic Hitchhikers! campaign, and volunteer organisations such as lake associations and neighbourhood/community groups, can have in providing education and effecting change. Similarly, however, research has also shown that participation in such schemes is more likely in the case of pre-existing perception and understanding of risks posed (Wolters, Steel, Weston, & Brunson, 2017). Continued understanding of the price impacts of disturbances, as one measure of the extent to which home-owners and -buyers recognise and capitalise potential costs, can inform development of funding arrangements for prevention and control measures, assuming that owners might be willing to pay some amount less than they might lose in the form of a tax or some other contribution towards those costs (e.g., in some kind of cost-sharing agreement with local, state/provincial and/or national entities).

Similarly, change is unlikely in the face of programs that protect homeowners from the full brunt of outcomes, i.e., that essentially cover the cost of events. In the case of wildfire, for example, emergency aid and the existence of homeowners insurance perhaps provide a sense of security which reduces the perceived risk of these events. Cessation of aid and/or removal of coverage would place the full cost onto homeowners, a factor which would presumably enter into home-buying decisions as the full extent of those costs was realised. This might not only reduce the prices and saleability of high risk properties, but eventually convince the public that some especially fire-prone locations are simply no longer safe enough in which to reside, thereby reducing the threat of damage not only to property but also to persons and their possessions. Relocation in response to climate change – also described as “planned retreat” – has been explored in a coastal context in Australia and Spain (Niven & Bardsley, 2013; Fatorić, Morén-Alegret, Niven, & Tan, 2017). Given evidence to suggest that even nearby events do not impact risk perceptions if they are not immediately visible, a finding for fire supported by studies of flood risk versus experience of actual inundation (Atreya & Ferreira, 2015), a disconnect still clearly exists between people’s perception of risk, and the reality of disturbances and their dangers; rather than subsidise homeowners for loss of value via compensation or insurance plans, government and the insurance industry should take an active stance in highlighting the risks and associated costs associated with residing in disturbance-prone zones. The positive and negative implications of climate change for the insurance industry are attracting increasing attention in the literature (e.g., Thistlethwaite & Wood, 2018).

6. LIMITATIONS AND NOTES FOR FUTURE RESEARCH

Though the review is comprehensive in its coverage of the topic, it is critical to acknowledge both the limitations of the hedonic technique, and of the sole focus on studies employing the hedonic approach. For example, the HPM does not include all use(r)s of property/resources, e.g., it does not incorporate consideration of the values lost to non-local users (including tourists and associated recreation-related spending, especially important to consider in resource-rich areas where tourism is often a substantial driver of the local economy) or costs to agriculture, industry and power generation (the latter of which can be heavily impacted by milfoil infestation). Similarly, the HPM does not capture non-use values (e.g., option, bequest, existence).

Only studies of residential properties were identified; there is apparently a complete lack of evidence regarding impacts on commercial, industrial, communal and publicly-owned properties. Those residential properties considered in the aquatic invasives studies also tended to include only those directly on the waterfront, thereby excluding impacts on surrounding though not directly adjacent homes. Though non-adjacent homes would not necessarily bear the brunt of visual impacts, their owners would nevertheless be afflicted by any negative impacts on recreational use. With respect to fire, actual damages to directly impacted (i.e., burned) properties were not included in any of the studies reviewed. As noted above, all studies identified were based in the US; it is quite likely that the existence and magnitudes of impacts vary geographically. Lastly, recent studies have emphasised the importance of functional form, and the consideration of spatial dependence and heterogeneity, in house price analyses. Montero, Fernández-Avilés and Minguez (2018), for example, compare twelve different (semi)parametric and (a)spatial models to estimate the effects of air and odour pollution in Madrid. This paper also notes the challenges associated with the choice of objective versus subjective measures of environmental factors, another issue of relevance to the body of work reviewed. Future hedonic analyses of the impacts of disturbances should consider these issues.

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Table 1. Impacts of Beetle Epidemics on Residential Property Values

Author (Year) *refereed	Study Site/ Location	Year(s) of Data	Method, Sample Size, (Adjusted) R^2 (as applicable and listed)	Dependent Variable(s), Average	Environmental Variable(s)	Key Findings Rega Environmental Var Values
Price, McCollum & Berrens (2010) *	Grand County, Colorado, USA	1995 to 2006	Spatial lag hedonic model (semi-log form) at three spatial scales (within 0.1, 0.5 and 1.0km of each property), 1,933 transactions	Sales prices of residential properties, mean $429,768	Number of trees killed by mountain pine beetle	Number of dead tr and negative in all values reduced by each dead tree with buffer, respectively
Hansen & Naughton (2013) *	Western portion of Kenai Peninsula, Alaska, USA	2001 and 2010	Four hedonic models (OLS, spatial lag, spatial error, spatial mixed) (semi-log form), 4,398 properties	Assessed values of single household residences, mean $166,254	Occurrence of spruce bark beetle outbreak, number of years since outbreak (1-5, 6-20), distance from outbreak (<0.1km, 0.1-0.5km, 0.5-1.0km)	Impact of outbreak insignificant. Impa 0.5-1.0 km signific increasing assessed ($6,162) and 2.1% Effects of outbreak increasing values b occurred in previou ($4,996) in previou

Table 2. Impacts of Terrestrial Invasives on Residential Property Values

Author (Year) *refereed	Study Site/ Location	Year(s) of Data	Method, Sample Size, (Adjusted) R^2 (as applicable and listed)	Dependent Variable(s), Average	Environmental Variable(s)	Key Findings Rega Environmental Var Values
Holmes, Murphy & Bell (2006) *	Sparta, New Jersey, USA	1992 to 2002	General spatial dependence hedonic models (semi-log form) at four spatial scales (parcel, within 0.1km, within 0.5km, within 1km), 3,379 transactions, 0.68-0.69	Sales prices of residential properties, median $382,180	Five classes of hemlock health (healthy/lightly defoliated, moderately defoliated, severely defoliated, dead, no hemlocks)	Effect of healthy h statistically signific models. Effect of m hemlocks negative significant (at ≤ 0.1 Effect of severely d insignificant in all dead hemlocks insi significantly positi
Holmes, Murphy, Bell & Royle (2010) *	West Milford, New Jersey, USA	1992 to 2002	Four hedonic models (cross-section with spatial error, cross-section with fixed effects, difference-in-difference with spatial error, difference-in-difference with fixed effects) at three spatial scales (parcel, within 0.1km, within 0.5km), 4,373 transactions, 0.60-0.67	Sales prices of residential properties, mean $177,752	Cross-section models: four classes of hemlock health (healthy/lightly defoliated, moderately defoliated, severely defoliated, dead); difference-in-difference models: area of hemlocks, threshold level of hemlock health	Parameter estimate hemlocks negative (at ≤ 0.10) in four c models, parameter specifying time per decline resulted in significant in five c difference specifica parcel ranged from Total economic los during the study pe million to $2.1 mil
Kovacs, Holmes, Englin & Alexander (2011) *	Fifty-six communities in Marin County, California, USA	1983 to 2008	Hedonic models (semi-log form) for two time periods: early invasion (1998-2003) cross-sectional spatial econometric models, full timeframe (1983-2008) quasi-experimental difference-in-differences models with fixed effects, 30,907 transactions, 0.68-0.75	Sales prices of single family homes, mean $958,355	Outbreak of sudden oak death (SOD) in late 1997 and subsequent presence/abundance of disease within various distances of properties	Property adjacent t temporary decline disappearing withi trees removed. Pro of SOD infested oa 6% decline in valu located throughout nearby woodland: for several years.

Table 3. Impacts of Aquatic Invasives on Residential Property Values

Author (Year) *refereed	Study Site/ Location	Year(s) of Data	Method, Sample Size, (Adjusted) R^2 (as applicable and listed)	Dependent Variable(s), Average	Environmental Variable(s)	Key Findings Regar Environmental Vari
Halstead, Michaud, Hallas-Burt & Gibbs (2003) *	Ten lakes in central New Hampshire, USA	1990 to 1995	Three hedonic models (linear and log forms), 144 lakefront properties, 0.58-0.68	Sales prices of properties, mean $170,557	Dummy variable to presence/absence of variable milfoil; interaction between presence of milfoil and lake size	Presence of milfoil price of $35,383 (21 (43%, log-linear) (la post correction for h Interaction term bet lake size positive an
Horsch & Lewis (2009) *	172 lakes in Vilas County, northern Wisconsin, USA	1997 to 2006	Nine cross-sectional and spatial difference-in-differences hedonic models (linear form), 457 (cross-sectional models) or 1,714-1,841 (spatial models) lakeshore properties, 0.75	Sales prices of properties, mean $268,035	Variables to represent presence/absence and relative frequency of Eurasian milfoil, interacted with occurrence of treatment prior to sale; dummy variables for sales prior to infestation and in prime milfoil months; water clarity	Effect of sale in prin insignificant in all m premium on treated property on a lake fr watermilfoil $28-32 $268,035). Invaded decrease in land val property values (lan after invasion. Effec and significant in cr
Zhang & Boyle (2010) *	Four lakes and one pond in Rutland County, Vermont, USA	1990 to 1995	Multiple hedonic models (with all-possible-regressions procedure), 65 lakefront properties (log of price, quadratic and exponential forms of vegetation cover), 0.64	Sales prices of single family houses and unimproved land, mean $108,661	Total aquatic macrophyte and Eurasian milfoil coverage of water surface in front of each property (measured on a six-point scale: <1%, 1-20%, 21-40%, 41-60%, 61-80%, 81-100%); water clarity	Amount of Eurasian insignificant, amoun macrophyte cover s increased (decrease (rose) by <1% to 16 incremental increas infestation. Water c
Johnson & Meder (2013)	Seventeen counties in north central Wisconsin, USA	2009 to 2011	Multiple hedonic models, 1,072 lakefront properties, 0.75	Sales prices of homes, mean $303,489	Presence of milfoil and of zebra mussels	Main models: prese and positive (10.0% insignificant; when model, both signific milfoil (-4.8%). Add mussels positive in even after controllin

Olden & Tamayo (2014) *	41 lakes (17 with milfoil, 24 uninvaded) in King County, Washington, USA	1995 to 2006	Three hedonic models (linear form), 1,258 lakeshore properties	Sales prices of single family homes, mean $502,313	Presence of Eurasian milfoil; water clarity	Presence of milfoil l impact on sales pric 19%). Marginal wil for waterfront prope on average $94,385 $4,719 (5% discoun milfoil invading one per year. Water clar
Tuttle & Heintzel-man (2015) *	52 lakes in Adirondack Park, New York, USA	2001 to 2009	Ten fixed effects hedonic models (log-linear form), five for all 12,001 parcels and five for 2,624 parcels within 0.05 miles of water, 0.44-0.55	Sales prices of residential parcels, mean $179,190	Presence/absence of loons; number of loons present; presence/absence of Eurasian water milfoil; annual average pH (<6.5 (poor), 6.5-8.5 or unknown)	Presence or number positive effect in all unknown pH consis negative. Presence o three of four cases, fourth case.
Liao, Wilhelm & Solomon (2016) *	Lake Coeur d'Alene, northern Idaho, USA	2010 to 2014	Six hedonic models (traditional OLS and spatial regime) (semi-log form), 614 lakefront properties, 0.57	Sales prices of single family homes, mean "approx." $500,000	Presence of Eurasian milfoil; water clarity	Presence of milfoil i 3/6 models (causing -13%), insignificant positive and signific
Gooden-berger & Klaiber (2016) *	Twin Cities, Minnesota, USA	1990 to 2005	Duration model of land conversion and hedonic model (log-log form), 448,209 sales	Undeveloped parcels of land on/near lakes	Introduction of Eurasian milfoil	Undeveloped parcel less likely to be dev invaded lakes, incre within 400m (both s lakefront parcels -18

Table 4. Impacts of Fire Risk on Residential Property Values

Author (Year) * refereed	Study Site/ Location	Year(s) of Data	Method, Sample Size, (Adjusted) R^2 (as applicable and listed)	Dependent Variable(s), Average	Environmental Variable(s)	Key Findings Rega Environmental Vari
Pricewater-house Coopers (2001)	Los Alamos, New Mexico, USA	1996 to 2001	Pre-post fire regression analysis	Sales prices of single family homes	Occurrence of Cerro Grande Fire (May 2000)	Average home price and 11% post fire (s
Loomis (2004) *	Pine, Colorado, USA	1993 to 2001	Pair of hedonic models (linear and semi-log forms), 504 sales, 0.50-0.52	Sales prices of houses	Occurrence of forest fire in nearby town of Buffalo Creek	Pre-post fire variab in both models, indi $17,095-$18,519 (1
Donovan, Champ & Butry (2007) *	Colorado Springs, Colorado, USA	1998 to 2004	Multiple hedonic models (traditional OLS, spatial lag, spatial error, combined) (log form), 9,903 sales (6,787 pre- and 3,116 post-publication), 0.63-0.87	Sales prices of houses, mean $244,00 pre-publication of risk ratings, $290,000 post publication	Publication of parcel-level wildfire risk ratings (low, medium, high, very high, extreme) by Fire Department	Pre-publication of v ratings had significa prices. Post-publica insignificant.
Huggett, Murphy & Holmes (2008)	Chelan County, Washington, USA	1992 to 1996	Hedonic model (difference-in differences, log-linear), 4,720 sales, 0.61	Sales prices of residential properties, mean $114,315	Distance to closest fire boundary	Prices dropped 13-1 large fires (1994), b Effect of distance n fires, positive and s fires, insignificant b
Mueller, Loomis & González-Cabán (2009) *	Los Angeles County, California, USA	1989 to 2003	Multiple hedonic models (log of sales, multiple forms of time variables, three distance cut-offs, 2,520 sales within 1.75 miles of at least one wildfire, 0.64	Sales prices of single family residences, mean $151,907	Number of wildfires, number of days since wildfire, distance from wildfire(s)	Significant drop in p second (-22.7%) wi distance cut-off redu miles, also robust in of days since first fi since second fire po all distance cut-offs double-log models)
Stetler, Venn & Calkin (2010) *	Northwest Montana, USA	1996 to 2007	Three hedonic models (semi-log form), 11,817 sales (4,173 with view	Sales prices of homes, mean $260,000	View of burned area, size of closest fire, distance from burned area, time between	For all properties: d significant negative (-13.7%) and 5-10k impact beyond 10kr

			of burned area, 7,644 without), 0.82-0.83		nearest fire and date sold	had significant nega fires had additional impact (-3.5%). Pri since nearest fire. N distance and fire siz increased in model with view of burned without such a view since nearest fire re
Hansen & Naughton (2013) *	Western portion of Kenai Peninsula, Alaska, USA	2001 and 2010	Four hedonic models (OLS, spatial lag, spatial error, spatial mixed) (semi-log form), 4,398 properties, 0.60	Assessed values of single household residences, mean $166,254	Occurrence of large (>3.3 hectares) and small (<3.3 hectares) wildfires, number of years since fire (1-5, 6-20), distance from fire (<0.1km, 0.1-0.5km, 0.5-1.0km)	Impact of large wil significant (positive spatial mixed mode 2/4 models in 0.1-0 (negative) in 1/4 mo Impact of small wil significant (negativ spatial mixed mode (positive) at 0.1-0.5 mixed model), insig Positive effects of l time, negative effec with time.
Rossi & Byrne (2016)	Boulder County, Colorado, USA	2008 to 2014	Four hedonic models (semi-log spatial Durbin), 5,000 transactions	Sales prices of houses, mean $199,280	Number of fires within 1.75 miles of property in 5 years prior to sale	Number of fires ins