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Future Land-Use Changes and the Potential for Novelty in Ecosystems of the United States

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Abstract

Rapid global changes due to changing land use, climate, and non-native species are altering environmental conditions, resulting in more novel communities with unprecedented species combinations. Understanding how future anthropogenic changes may affect novelty in ecosystems is important to advance environmental management and ecological research in the Anthropocene. The main goal of this study was to understand how alternative scenarios of future land-use change may affect novelty in ecosystems throughout the conterminous United States. We used five spatially explicit scenarios of future land-use changes, reflecting different land-use policies and changes in agricultural markets, to quantify and map potential drivers of novelty. Our results showed large areas where future land-use changes may increase novelty in ecosystems. The major land-use changes known to increase novelty, including land abandonment and land-use expansion, were widespread in all scenarios (73 million to 95 million ha), especially in the eastern U.S. and along the West Coast. Our scenarios revealed that, at broad scales, future land-use changes will increase novelty in ecosystems, and that traditional conservation policies may have limited ability to prevent the process. In places such as the eastern U.S., conserving and maintaining historical conditions and associated biological diversity may become increasingly difficult due to future land-use changes and related ecological factors. Successful biodiversity conservation and environmental management in the Anthropocene will require novel conservation approaches to be relevant in areas with high levels of novelty in ecosystems.

Key words: novel ecosystems; land-use change; global change; biodiversity; Anthropocene; scenarios.

Introduction

Human activities related to land use, climate change, and the spread of non-native species are altering environmental conditions and composition of communities, resulting in rising novel ecosystems (Hobbs and others 2006; Williams and Jackson 2007; Ellis 2011; Radeloff and others, in press).

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Ecosystems with high biotic novelty pose difficult questions for environmental management and research, as attempts to return biological diversity to historical benchmarks may no longer work (Lindenmayer and others 2008; Seastedt and others 2008; Hobbs and others 2009). It is expected that novelty in ecosystems will increase under future global change, potentially affecting biodiversity patterns and ecosystem services worldwide (Lugo 2013; Radeloff and others, in press). However, our understanding of future levels of novelty in ecosystems is limited. Predicting how future scenarios of anthropogenic change could influence ecological novelty can provide important information for ecological research and environmental management in the Anthropocene.

Novelty in ecosystems can stem from multiple causes (Radeloff and others, in press), but we focus here on novelty due to land-use change. Species composition in highly novel ecosystems is different from that of historical systems as a result of the presence of non-native species and biotic responses to changing environmental conditions, such as habitat degradation, modification of soil properties, or climate change (Hobbs and others 2006). The species composition of highly novel communities includes combinations of native and non-native species, or native species in different abundances relative to historic communities.

Common places where ecosystems are highly novel include those that have been abandoned after intensive human use, as well as semi-natural spaces imbedded within and at the border of human-dominated land uses (Perring and others 2013). Examples include abandoned croplands, remnants of former wildlands within cities or within agricultural landscapes, patches of wild vegetation in the limits of urban areas or crop fields, brownfields, and transportation and transmission corridors, among others. These places typically have a high abundance of non-native species, simplified native vegetation, and altered wildlife communities (McKinney 2002; Chace and Walsh 2006; Duguay and others 2006).

Land-use change is one of the major drivers of global change, and also a cause of novelty in ecosystems (Hobbs and others 2006). As former farm fields and pastures are left fallow for extensive time periods, for example, natural vegetation can recover naturally. However, changes in soil conditions from past land-use practices (for example, erosion or salinization), limited seed sources for native species, introduced species, and altered disturbance regimes can change the path of recovery and increase novelty (Hobbs and others 2006; Cramer and others 2008). In the U.S., for example, grasslands that previously were agricultural lands typically contain lower plant diversity and more introduced species than grasslands that have never been cultivated (Baer and others 2002, 2009; Elmore and others 2007). In the northeastern U.S., forests that recovered after large agricultural clearings show abundances of native species that are dramatically different from pre-colonial conditions (Thompson and others 2013). In Puerto Rico, agricultural abandonment in the 1940s, and subsequent vegetation recovery, resulted in forests with a large presence of non-native species that are resilient to hurricanes (Lugo 2004). In the future, intensification of agriculture and rapid environmental change are expected to lead to an increasing number of old-fields with little evidence for a long-term trends towards historical vegetation communities (Cramer and others 2008).

The expansion of human land uses (for example, houses, croplands, and so on) into natural areas typically fragments habitats, isolates wild populations, and alters soil conditions, changing ecological communities, and the native biota (Fahrig 2003), thus providing opportunities for novelty (Perring and Ellis 2013). At the same time, the expansion of human land uses facilitates the spread of non-native species into natural areas. Fragmentation creates edges that act as dispersal points for non-native species into surrounding landscapes (Bradley and others 2010; Vilà and Ibáñez 2011), and landscaping around houses provides a source of non-native plants than can spread to surrounding disturbed environments (Gavier-Pizarro and others 2010b). Indeed, the frequency of non-native species in a given area of land is strongly related to the diversity and intensity of human land uses in the surrounding landscape (Tyser and Worley 1992; Bradley and Mustard 2006; Gavier-Pizarro and others 2010a). As human land uses expand into natural areas, novelty in ecosystems is likely to rise due to habitat degradation and species invasions (Hobbs and others 2006).

Predictions of future land-use changes could therefore help quantify key drivers of novelty in ecosystems and provide insight into patterns of novelty in the Anthropocene. However, when assessing future environmental changes, it is important to examine multiple scenarios rather than a single forecast, to understand the range of potential outcomes and how human decisions may affect them (Polasky and others 2011). In terms of land-use changes, for example, payments for ecosystems services, land-use zoning regulations, and changes in crop commodity prices are important factors affecting landowners' land-use decisions, and consequently future land-use patterns and ecological processes. Land-use data have proved useful for assessing current and past distribution of novelty in ecosystems (Martinuzzi and others 2013a; Perring and Ellis 2013), and spatially explicit scenario analyses provide a powerful tool to assess future conditions.

The main goal of our study was to understand how alternative scenarios of future land-use change may affect novelty in ecosystems across the conterminous U.S. We used spatially explicit scenarios of future land-use changes reflecting different land-use policies and changes in agricultural markets to quantify and map drivers of novelty in ecosystems. Specifically, our objectives were to (1) quantify the magnitude of drivers of novelty in ecosystems under different scenarios of future land-use change; and (2) evaluate the geographic patterns of those drivers. We discussed how future changes in land use, land-use policies, and economic conditions may affect major drivers of novelty in ecosystems, and discussed where novelty is more likely to increase. We did not map future levels of novelty in ecosystems, as the data to do so do not exist. Instead, we gained an understanding of ecological novelty by studying one of its major and well-documented drivers, land-use change.

Materials and Methods

Data and General Approach

Our approach consisted of linking spatially explicit land-use change projections to major land-use drivers of novelty in ecosystems, specifically land abandonment and land-use expansion. We used the term *land abandonment* to refer to areas of crop and pastures that convert to natural vegetation cover (forest and natural grasslands and shrublands) after active land use ceases or decreases in intensity. We used the term *land-use expansion* to refer to areas of natural vegetation that convert to human land uses (urban, crop, and pasture). This reflects the expansion of human land uses into natural habitat, which is associated with increased risks of both habitat degradation and the spread of non-native species. Land conversions that do not meet these criteria are not part of our definitions. A recent paper by Murcia and others (2014) criticized the definition of novel ecosystems by Hobbs and others (2006), in particular the statement that novel ecosystems are irreversible and cannot be restored. Our definition of novelty is broader than that of Hobbs and others (2006) in that it does not consider reversibility, and allows novelty to vary along gradients.

We used spatially explicit scenarios of future land-use changes (2001–2051) for the conterminous U.S. from Lawler and others (2014). These scenarios are based on an econometric model that estimates the probability of conversion among five different land-use categories, including urban, crop, pasture, forest, and natural rangelands (that is, natural grasslands and shrubs), based on observed landowner decisions in response to economic conditions. The model was parameterized with about 800,000 observations of past land-use changes from the 1990s from the U.S. Department of Agriculture's National Resources Inventory, and information about economic returns for different land uses depending on soil quality (Radeloff and others 2012). For each combination of land-use type, soil characteristics, and county-level economic return, the model quantifies the probability of land-use change between 2001 and 2051 using a multinomial logit function from Lubowski and others (2006). The model forecasts land-use changes at a spatial resolution of 1-ha, and only private lands are allowed to change in land use. Public lands, mostly in the western half of the country, are assumed to remain in the same use as in 2001. The econometric model was validated using hypothesis tests as part of the econometric estimation detailed in Lubowski and others (2006). Our model did not take climate change into account; however, land-use patterns during the date of our projections are expected to be shaped largely by land-use trends such as urbanization, with climate change having a relatively small influence (Haim and others 2011).

A major benefit of econometric-based models is that they are able to simulate the effect of potential future policies or changes in economic conditions that could modify the economic returns to different land uses, and thus, the probabilities of land conversion (Radeloff and others 2012). We analyzed five scenarios of future land-use change following Lawler and others (2014), including a Business-as-Usual scenario, three conservation-policy scenarios, and one scenario based on changes in crop market conditions. These scenarios are intended to simulate relatively strong conservation policies and trends in crop demand reflective of the recent past, and have proved useful for quantifying the effects of future land-use change for biodiversity-rich areas (Martinuzzi and others 2013b), freshwater conservation (Martinuzzi and others 2014), and protected areas (Hamilton and others 2013).

- The Business-as-Usual scenario reflects a continuation of recent land-use change trends (based on 1990s) to 2051.
- The Forest Incentives scenario provides incentives for afforestation and reduced deforestation, similar to carbon sequestration incentives. Landowners are paid $247/ha/year if they convert land to forest, and are taxed $247/ha/year for land if they deforest. A $247/ha/year subsidy translates into a $50/ton carbon price, a relatively aggressive carbon policy (Lubowski and others 2006).
- The Native Habitat scenario provides incentives for the conservation of natural habitats, including forest and rangeland. Landowners are taxed $247/ha/year on land that they convert from natural land cover to a more intensive land use (urban, crop, or pasture).
- The Urban Containment scenario reflects the implementation of ''smart-growth'' zoning regulations to reduce urban sprawl, by prohibiting the conversion of land to urban in non-metropolitan counties (as defined by the U.S. Census).
- The High Crop Demand scenario assumes substantial growth in the demand for agricultural commodities with concomitant pressures to expand agricultural lands. Crop commodity prices are assumed to rise by 160% by 2051, resembling a recent period of very high crop commodity prices (2007–2012).

The results of our study are projections, not predictions. Our Business-as-Usual scenario reflects what land-use patterns would look like by 2051 if conditions from the 1990s, when the model was parameterized, were to persist (Radeloff and others 2012; Lawler and others 2014). This is an assumption, not a claim that those conditions are likely to persist. Our projections are not intended to predict events such as the housing bubble and recession in the late 2000s, nor the ''right'' future, or the exact actual conditions. The Business-as-Usual scenario is a way of constructing a view of the future against which we can evaluate the influences of economic and policy changes, and learn about the consequences of future land-use changes in the context of novelty in ecosystems.

Magnitude of Land-Use Expansion and Land Abandonment

We summarized three aspects of the extent (ha) of the driving forces of novelty in ecosystems based on land use. First, we calculated the total area (ha) of land-use expansion plus land abandonment for each scenario. This provided an indicator of the magnitude of a major force causing novelty in ecosystems. Second, we compared the area of land-use expansion (ha) versus the area of land abandonment (ha) for each scenario, which provided an indicator of the relative importance of our two drivers of novelty in ecosystems. Third, we summarized the total area (ha) of the different types of land-use changes that cause land-use expansion and land abandonment to understand which types of internal changes are ultimately driving novelty in ecosystems. In this sense, we reported the total area of land-use expansion into natural habitats expected as a result of urban expansion, crop expansion, and pasture expansion. For land abandonment, we reported the area of crop abandonment and pasture abandonment, where abandonment means conversion into natural vegetation cover.

Geographic Patterns of Land-Use Expansion and Land Abandonment

To evaluate geographic patterns, we summarized land-use changes across the conterminous U.S. using a 10-km grid, which is an effective scale for visualizing land-use patterns across the nation (Lawler and others 2014). For this, we added the land-use values for the 1-ha pixels found in each 10-km pixel. We quantified similar measures as those summarized above, but analyzed them spatially. First, we mapped the relative area of land-use expansion plus land abandonment per pixel (that is, percent cover by 10-km pixel) to depict the geographic patterns of land-use changes shaping novelty in ecosystems. Second, we mapped the percent cover of land-use expansion versus the percent cover of land abandonment per pixel, which depicted the relative importance of the two drivers of novelty in ecosystems. Third, we evaluated spatial patterns of the most important of our drivers of novelty in ecosystems by calculating the dominant (that is, most extensive) type of land-use change for each pixel (for example, land-use expansion due to urban expansion, crop abandonment, and so on).

Results

Magnitude of Land-Use Expansion and Land Abandonment

Our two drivers of novelty in ecosystems, that is, land-use expansion and land abandonment, were

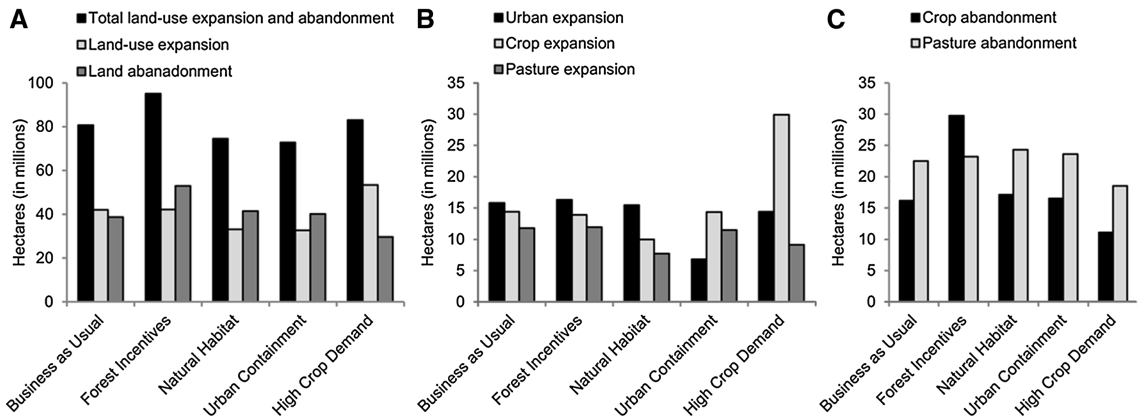

Figure 1. Area (ha) of land-use expansion and land abandonment projected under different scenarios of future land-use change (**A**), including the extent of the different land-use changes associated with land-use expansion (**B**) and land abandonment (**C**).

projected to cover substantial amounts of land by 2051, and this was true for all scenarios. Under the Business-as-Usual scenario, the total area of land-use expansion plus land abandonment covered 81 million ha (or 11% of the total U.S. land, an area larger than Texas; Figure 1A). The other scenarios showed overall small differences compared to Business as Usual. The Forest Incentive scenario, for example, had the largest area of total land-use expansion plus land abandonment projected among scenarios, equal to 95 million ha (18% more than Business as Usual), whereas the other scenarios ranged between 73 and 83 million ha (that is, within 10% of Business as Usual; Figure 1A).

Although the total area of land-use expansion plus land abandonment did not vary much under the different scenarios, the relative importance of those drivers of novelty did vary considerably. Under the Business-as-Usual scenario, land-use expansion and land abandonment were projected to cover very similar amounts of land, with land-use expansion being slightly more common than land abandonment (9% more area; Figure 1A). In contrast, under the High Crop Demand scenario, the area of land-use expansion was projected to be almost twice as large as the area of land abandonment (80% more; Figure 1A). In addition, whereas the Business-as-Usual and High Crop Demand scenarios resulted in more land-use expansion than abandonment, the scenarios that reflect conservation policies, that is, Forest Incentives, Natural Habitat, and Urban Containment, resulted in less land-use expansion than land abandonment (about 20% less; Figure 1A).

The relative importance of the different land-use change processes associated with land-use expansion and land abandonment also varied considerably across the different scenarios, affecting the ultimate drivers of novelty in ecosystems. Under the Business-as-Usual, Forest Incentives, and Natural Habitat scenarios, urban expansion was the main driver of future land-use expansion, followed by crop expansion, and then by pasture expansion. Under the High Crop Demand and the Urban Containment scenarios, on the other hand, crop expansion was the main driver of land-use expansion, followed by urban or pasture expansion depending on the scenario (Figure 1B). For land abandonment, on the other hand, in almost all scenarios the main driver was the abandonment of pasture lands followed by the abandonment of crop lands, and the amount of pasture abandonment was relatively constant across scenarios (Figure 1C). The only exception was the Forest Incentives scenario, in which the main driver of land abandonment was the abandonment of crop lands followed by pastures.

Spatial Patterns of Land-Use Expansion and Land Abandonment

Novelty in ecosystems due to land-use change was projected to be particularly likely in the eastern half of the U.S. and along the West Coast, a pattern common to all scenarios (Figure 2). Practically the entire eastern U.S. was projected to experience some level of land-use expansion or abandonment, typically between 10 and 40% of our 10-km pixels. Regions with the highest rates of total land-use expansion or abandonment were located in the southeastern Great Plains (that is, the south-central U.S.), in some parts of the Northeast (states like

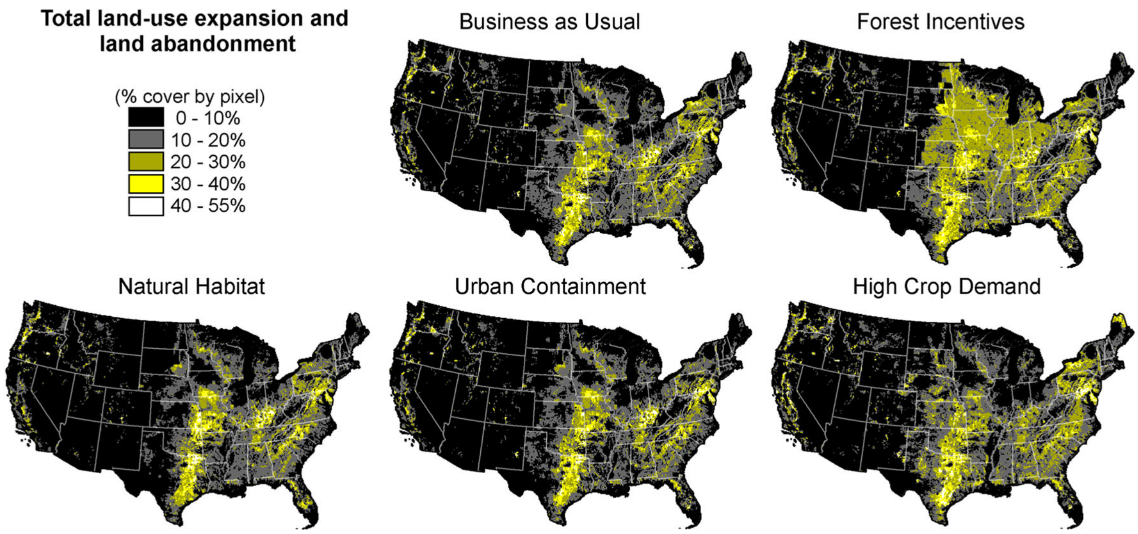

Figure 2. Spatial patterns of total land-use expansion and abandonment across the conterminous U.S. under different scenarios of future land-use change. Larger versions of the maps are included in Online Appendix.

Pennsylvania, New York, New Jersey), along the Southeastern Plains (in the southeastern U.S.), and in interior valleys of the West Coast (California, Oregon, Washington; Figure 2). The Forest Incentives scenario also showed a high potential for novelty in ecosystems in the Upper Midwest. The western half of the country, which has a large amount of public lands, showed low rates of land-use expansion and/or abandonment, as public lands were held constant by our model.

The relative importance of our two drivers of novelty in ecosystems, land-use expansion, and land abandonment, also varied across the country. Under Business-as-Usual conditions, for example, regions like the Midwest experienced higher levels of land abandonment than land-use expansion. The Southeast and parts of the East coast, on the other hand, were projected to experience higher levels of land-use expansion than abandonment (Figure 3A). The West was projected to experience both land-use expansion and land abandonment depending on the region. The other scenarios showed variations of these patterns. The Forest Incentives scenario, for example, increased the rates of land abandonment in the Midwest, whereas the High Crop Demand scenario increased land-use expansion in the Southeast and central U.S., while reducing the rates of land abandonment in the Midwest (Figure 3A).

Lastly, the types of land conversions resulting in land-use expansion (urban expansion, crop expansion, pasture expansion) and land abandonment (crop abandonment, pasture abandonment) varied considerably across space (Figure 3B). Along the Southeast coast, for example, the main drivers of novelty in ecosystems changed from urban and crop expansion in the Business-as-Usual scenario, to mostly crop abandonment in the Forest Incentives, and to mostly crop expansion under the High Crop Demand scenario. In South-central U.S., either pasture expansion or crop expansion was the main driver depending on the scenario (Figure 3B).

Discussion

Our results highlighted that future land-use changes will likely facilitate the presence of novelty in ecosystems in many parts of the conterminous U.S. Two of the major causes of novelty, that is, land-use expansion into natural habitats and land abandonment, were predicted to cover large areas of lands by 2051 and to be widespread across the country, and this was true in our five scenarios of future land-use change. Overall, our findings revealed that future land-use changes will likely provide suitable conditions for increases in novelty despite shifts in socioeconomic conditions, potentially affecting future biodiversity and ecosystem services patterns across the U.S.

We showed that large parts of the U.S. will provide suitable conditions for rising novelty in ecosystems, particularly in the eastern half of the country and in some parts along the West Coast. These findings are not trivial, as the presence and distribution of some of these areas coincide with the presence of other ecological factors that can

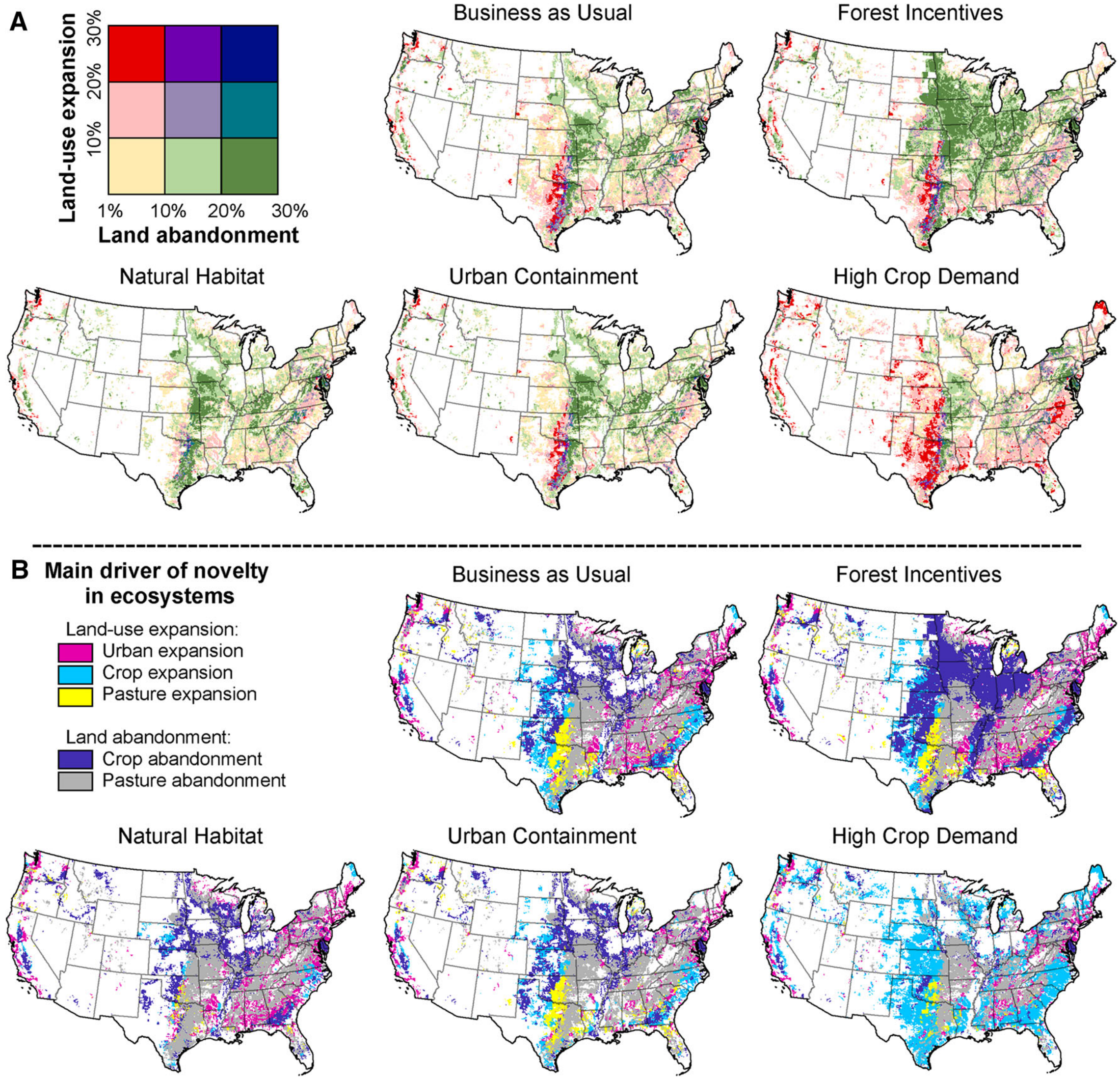

Figure 3. Distribution of land-use expansion versus land abandonment across the conterminous U.S. under different scenarios of future land-use change (**A**). The *bottom* figure shows the main land-use change driver of land-use expansion and land abandonment respectively, calculated at the pixel level (**B**). Only pixels with greater than 10% cover of total land-use expansion and/or abandonment are shown. Larger versions of the maps are included in Online Appendix.

favor novelty in ecosystems, including the abundance of introduced species of plants and animals (for example, Northeast, West Coast; Stohlgren and others 2006), the distribution of the wildland-urban interface (for example, Southeast, Northeast; Radeloff and others 2005), and the presence of highly fragmented habitats (for example, Southeast; Riitters and others 2002). For instance, the U.S. Forest Service Forest Inventory and Analysis Program has already documented the naturalization of many introduced tree species in eastern U.S. forests (Potter and Smith 2012), resulting in novel forests and an increase in the number of tree species. At the same time, the historical tree species community in the region has changed as a result of non-native pathogens and human actions, with conifer and oak species being replaced by aspen and maple (Schulte and others 2007; Nowacki and Abrams 2008; Rogers and others 2008), and this change is affecting animal communities (Rodewald and Abrams 2002; Mcshea and others 2007; Wood and others 2012). Furthermore, current land-use patterns suggest that there are already novel ecosystems in these regions (Perring and Ellis

2013), and the eastern U.S. has been identified by Bellard and others (2013) as a geographic area where the future establishment of introduced species is likely due to climate and other environmental change. The combinations of these factors will likely increase the number of species and variety of habitats, and increase novelty in this region.

The implementation of conservation policies and changes in crop markets may alter the direction of future land-use changes in some regions, and shift the relative importance of the potential drivers of novelty in ecosystems. However, at the national scale, the result from all of our scenarios was that there were always large areas of land-use change known to be suitable for the potential development of novelty in ecosystems. The main lesson from our scenarios is that, at broad scales, future land-use changes will likely favor the rise of novelty in ecosystems, and land-use policies may have limited ability to affect that process. Even under strong conservation policies (for example, our Urban Containment scenario), the forces shaping novelty in ecosystems are likely to be present and widespread. Successful biodiversity conservation and environmental management in the future will require a clear understanding of the conservation opportunities and threats that novelty entails, in particular related to the provision of ecosystems services and habitat for native species.

Ultimately, the rise of novelty due to changes in species composition will depend on multiple ecological variables working together, such as the characteristics of the landscape matrix, type of land conversion, the temporal scale considered, and the processes and species involved. Usually, abandonment can lead to a faster rise of novelty, and often across large areas. For example abandonment of agricultural fields in Puerto Rico resulted in widespread secondary forests dominated by non-native *Leucaena leucocephala* (Grau and others 2003; Molina Colón and Lugo 2006). In addition, novelty is more likely to rise if the process of land abandonment occurs in a matrix dominated by human land uses (Hobbs and others 2006). For example, historical analysis of Eastern U.S. forests showed that secondary forests recovering in landscapes with mostly (>56% cover) agricultural lands are today more different in terms of species composition than those recovering in landscape with historically less human presence (Thompson and others 2013). In our study, most (70%) of all crop abandonment and half of all pasture abandonment was projected to occur in areas that are dominated by human land uses (that is, areas with ≥50% cover of human land use), reinforcing the presence of suitable conditions for novelty (see Supplementary material for the analysis on landscape matrix).

The intensification of land use and land-use expansion often leads to changes in the native biota and establishment of introduced species, favored by habitat fragmentation, degradation of ecosystems, and changes in natural disturbance regimes (Vitousek and D'Antonio 1997; Theoharides and Dukes 2007). However, in the case of land-use expansion, the rise of novelty can be either slow or fast depending on the type of expansion. For example, agricultural systems can create conditions favorable for non-native plants that in turn can invade adjacent ecosystems or spread after crop abandonment. Yet, novelty can rise also rapidly, for example, when land-use expansion is mediated by the colonization of non-native grasses, as occurred in California (Eliason and Allen 1997). In the case of urban expansion, however, there is often a time-lag between the time of settlement and the spread of non-native species into the surrounding habitats (Sullivan and others 2005). In our case, about 80% of our land-use expansion was projected to occur in areas that are also high in natural vegetation (see Supplementary material), suggesting that many ''wild'' areas may become more novel in the future. Regions where all scenarios agreed with regards to the potential changes expected, such as parts of California, Washington and Oregon, a large proportion of Kentucky, and several important spots in the East Coast states and New England, might deserve special attention in future management plans as they also coincide with widespread wildland–urban interface, high richness of non-native plants, and high forest fragmentation. Regions dominated by human land uses (especially by urban lands) or experiencing changes involving multiple anthropogenic activities (for example, urbanization, agriculture, and so on) are likely to see the strongest increases in ecosystem novelty.

Our study is one of the first to evaluate the likelihood of rises in novelty due to land-use change and under different land-use change scenarios, and as such is useful for understanding the environmental consequences of human actions in the Anthropocene. Previous efforts used the spatial arrangement of land uses to map the distribution of novel ecosystems by identifying ''pockets of unused lands in used areas'' as surrogates for novel ecosystems (Perring and Ellis 2013). Our study represents an advancement in that we analyzed key driving forces of novelty in ecosystems (Hobbs and others 2006). However, our results only provide a partial view of the future of novelty in ecosystems. We examined the potential for novelty in ecosystems due to land-use changes, yet other environmental forces, such as climate change and the spread of non-native species (for example, tamarisk [*Tamarix* spp.] and Scotch broom [*Cytisus* spp.] in the West) can also increase novelty in U.S. ecosystems regardless of land-use change (Williams and Jackson 2007; Bradley and others 2010; Radeloff and others, in press). Similarly, life zone conditions and altitude can affect whether novelty is due to changes in the abundance of native or introduced species, yet we did not examine that. In addition, our land-use projections did not consider transitions from urban into natural vegetation cover, which can also result in novelty in ecosystems (''urban wilderness''). However, this occurrence was so rare in our land-use change data that there was not enough empirical evidence to model this process. Similarly, local restoration efforts can reduce novelty, but we were not able to predict restoration efforts. Furthermore, our land-use model is not suitable for reflecting the spatial configuration of the different land uses at fine scales (Radeloff and others 2012), which limits our ability to infer ecosystem novelty based on changes in fragmentation or edge density. Similarly, our land-use model did not distinguish between different forest management practices, such as afforestation for managed plantations or natural succession. As a result, our measures of land abandonment may have overestimated the area where novelty in ecosystems is likely to rise.

Finally, our land-use estimates are useful to evaluate drivers of novelty in ecosystems under future anthropogenic changes, yet they are not intended to predict the future extent of highly novel ecosystems. In our study, a land-use change pixel is not synonymous with a highly novel ecosystem pixel. For example, an urban pixel expanding into natural habitat is considered a driver of novelty in ecosystems. However, urban land-use pixels are mostly likely composed of houses, built-up surfaces, roads, and lawns. In this context, novelty could rise in the natural habitats around (or embedded within) those new urban pixels, but our data are not detailed enough to quantify those. On the other hand, a pixel of crop changing into natural vegetation could potentially represent an entire pixel of a highly novel ecosystem. Thus, although it was tempting to predict the extent of highly novel ecosystems, our land-use numbers were not suitable for that.

The rise of novelty in ecosystems emerging from rapid global changes challenges environmental management and scientific research. Our study focused on the U.S. shows that future land-use changes are likely to facilitate the rise of novelty in ecosystems across landscapes, and under changing socioeconomic conditions. Successful environmental management and biodiversity conservation in the future will require a clear understanding of the role of novelty in ecosystems, particularly as it relates to the provision of ecosystems services for humans and habitat for native species.

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