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ORIGINAL ARTICLE

Simulating and delineating future land change trajectories across Europe

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Abstract Explorations of future land use change are important to understand potential conflicts between competing land uses, trade-offs associated with particular land change trajectories, and the effectiveness of policies to steer land systems into desirable states. Most model-based explorations and scenario studies focused on conversions in broad land use classes, but disregarded changes in land management or focused on individual sectors only. Using the European Union (EU) as a case study, we developed an approach to identifying typical combinations of land cover and management changes by combining the results of multimodel simulations in the agriculture and forest sectors for four scenarios from 2000 to 2040. We visualized land change trajectories by mapping regional hotspots of change. Land change trajectories differed in extent and spatial pattern across the EU and among scenarios, indicating trajectory-specific option spaces for alternative land system outcomes. In spite of the large variation in the area of change, similar hotspots of land change were observed among the scenarios. All scenarios indicate a stronger polarization of land use in Europe, with a loss of multifunctional landscapes. We analyzed locations subject to change by comparing location characteristics associated

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with certain land change trajectories. Results indicate differences in the location conditions of different land change trajectories, with diverging impacts on ecosystem service provisioning. Policy and planning for future land use needs to account for the spatial variation of land change trajectories to achieve both overarching and location-specific targets.

Keywords Land use change · Land system · Modeling · Scenario · Europe · Ecosystem service

Introduction

Land systems undergo constant change in response to a wide array of economic, environmental, institutional, and societal drivers (Geist et al. 2006; van Vliet et al. 2015). In recent decades, population growth and changing consumption patterns have led to a worldwide expansion and intensification of land use, potentially increasing the pressure on natural systems and the ecosystem services they provide (DeFries et al. 2004; Millenium Ecosystem Assessment 2005; Lambin and Meyfroidt 2011). These trends will likely continue in the future, as demand for land-based goods and services will increase drastically due to population growth, more meat-based diets, and a growing role of bioenergy (Lotze-Campen et al. 2010; UNECE-FAO 2011; Alexandratos and Bruinsma 2012). Understanding the land use outcomes of these trends is important (Rounsevell et al. 2012).

Substantial uncertainty exists as to how land use patterns in particular regions will change due to these trends. A range of location factors, including environmental conditions (e.g., topography, soil fertility), socioeconomic settings (e.g., distribution of income), spatial planning (e.g., nature conservation), as well as policies and trade, all exert strong influences in shaping land use responses to changing demands. Exploring future land use patterns is critical for anticipating possible negative impacts, identifying potential conflicts between competing land functions, and developing sustainable land use strategies to mitigate these (Verburg et al. 2006; Fürst et al. 2013; Seppelt et al. 2013). Land use modeling based on salient, credible, and legitimate storylines is a fundamental tool for exploring possible futures of land use change (Brown et al. 2013), and a wide range of models is currently available (Sleeter et al. 2012; Mas et al. 2014; Tayyebi et al. 2014).

Most studies to date have focused only on transitions among broad land cover classes (e.g., the conversion of forest into agriculture; Ramankutty and Foley 1999; Sohl and Sayler 2008; Verburg et al. 2009), while more subtle land use changes are omitted. Globally, and particularly in Europe, however, not only drastic land conversions, but specifically widespread land management changes constituted for a large share of land use change over the last decades (Stoate et al. 2001; Erb et al. 2013; Kuemmerle et al. 2013). Moreover, land management change impacts ecosystem service provisioning and biodiversity in substantial ways (Tscharntke et al. 2005), yet despite these possibly large impacts, land management change remains understudied (Erb et al. 2013; Luyssaert et al. 2014). Additionally, there are important feedbacks between land cover conversions and management changes. For example, changes in the management intensity influence yields and thus the required area for that land use (Matson and Vitousek 2006). Moreover, land management changes in forests and agricultural systems are often addressed separately and not integrated within the landscape context (Rounsevell et al. 2012). For a comprehensive interpretation of land change, it is essential to integrate land management change into land change modeling studies.

Identical local land cover or land management changes can have different drivers and consequences in different contexts or at different scales of analysis. For example, locally, the conversion of cropland to forest can indicate land abandonment and a decrease in the importance of agriculture. At the regional scale, however, such conversions may be associated with intensification of land management on more suitable locations and, thus, a polarization of rural land use (Plieninger et al. 2014). This illustrates how the consideration of multiple scales during the analysis can help to address and disentangle multiple land change trajectories and deepen the insights gained from land use change scenarios. Approaches that assess land use change at various scales and that jointly consider land cover and management changes are needed. The co-occurrence of different land change trajectories in the European Union (EU) has led to concerns for policy and planning (Renwick et al. 2013; van Zanten et al. 2014). This study focusses on identifying potential future land change trajectories for the EU.

The objective of this study was to integrate and interpret the results of consistent, multimodel, scenario simulations of both land cover and land management change in terms of typical land change trajectories at the extent of the EU. First, we create a typology of different land change trajectories based on the extent and regional patterns of simulated land use change. Second, we explore the complexity of interacting land use changes across scales for four alternative scenarios of land use change between 2000 and 2040. Third, we characterize the locations which are affected by particular land change trajectories in terms of their location characteristics and discuss the potential consequences of future land change in terms of their impact on current levels of ecosystem service provision.

Materials and methods

We integrated the results of a suite of models which account for demographic, economic, and environmental drivers across the EU (excluding Croatia) to map both land cover and land management change (Sect. 2.1). We then developed a typology of land change trajectories and summarized hotspots of occurrence of these land change trajectories across the EU following an expert-based hierarchical approach (Sect. 2.2). Finally, we analyzed the location characteristics of areas affected by land change trajectories (Sect. 2.3).

Land cover and land management scenarios

We simulated land use change in Europe between the years 2000 and 2040 for a set of exploratory scenario storylines that reflect socioeconomic, cultural, political, and technological changes in the EU. The four scenario storylines follow closely the IPCC SRES framework (Nakicenovic et al. 2000), but the drivers were modified to represent the conditions specific to the EU and were supplemented with conditions that address land use change in the European context. Importantly, our scenarios differed in their degree of regionalization versus globalization, and the extent of policy intervention (Table 1). Detailed scenario storylines are found in the Supplementary Material, Annex A.

To implement these storylines in simulations of future land cover and land management, we used a chain of models that exchange information in a top-down, hierarchical manner (Fig. 1). By implementing scenario conditions (Table 1), global models calculated changes in gross domestic product, required areas for food, feed and bioenergy crops, and wood production (Kallio et al. 2004; Lotze-Campen et al. 2008; Luderer et al. 2013; Woltjer and Kuiper 2014). The simulations from these global models were fed into different regional models that calculated urban land demand, crop-specific fertilizer use, livestock numbers, and potential supply of woody biomass from European forests at the national or subnational level (Britz and Witzke 2012; Lotze-Campen et al. 2014; Sallnäs 1990; Schelhaas et al. 2007; Verkerk et al. 2011). We then disaggregated the simulation outcomes to the grid level (1 km^2) using a land cover allocation model at yearly time steps from 2000 to 2040. Land cover was represented in 16 land cover categories (Table S2). A detailed description of the land cover allocation procedure can be found in Verburg and Overmars (2009).

Indicators for the management intensity of cropland, pastures, and forests were derived from the sectorial model outputs. To create maps of management intensity of cropland, we used nitrogen-based fertilizer use as a proxy.

Table 1 Scenario storylines

Scenario	Storyline
Libertarian Europe (V-A1)	Globalizing world with strong economic growth
	Global free trade
	Moderate population growth
	Absent or weak regulation policies
	No climate change adaptation and mitigation
Eurosceptic Europe (V-A2)	Fragmented world with modest economic growth
	Trade protectionism
	Strong population growth
	Weak regulation of land use change
	No climate change adaptation and mitigation
Social Democracy Europe (V-B1)	Sustainable world with modest economic growth
	Global free trade
	Modest population growth
	Strong policy interventions
	Global implementation of ecosystem service concepts and treaties for climate change adaptation and mitigation
European Localism (V-B2)	Fragmented world with modest economic growth
	Regional markets
	Modest population growth
	Moderate policy intervention
	Environmental objectives are implemented regionally

Nitrogen input links to agro-biodiversity and is therefore often used as a proxy for agricultural intensity (Overmars et al. 2014). We disaggregated fertilizer use (kg/ha) at NUTS2 level to the 1 km^2 grid following the approach of Temme and Verburg (2011), implemented for the full EU territory by Overmars et al. (2014). This disaggregation assigned a level of land use intensity to all cropland: low (0–50 kg/ha), moderate (>50–150 kg/ha), and high (>150 kg/ha) fertilizer use (Fig. 1). We used grazing intensity of cattle, goats, and sheep as a proxy for nitrogen inputs on pastures as suggested by Temme and Verburg (2011). We converted livestock numbers on NUTS2 level to livestock units (LSU) following Neumann et al. (2009). We disaggregated LSU to livestock density (LSU/km^2) based on grazing probability maps (Neumann et al. 2009) and reclassified the result into two classes, which were used as a proxy for low (0–25 LSU/km^2) and high (>25 LSU/km^2) grazing intensity (Fig. 1).

For forest management, we used wood removals, which reflect the use intensity of forests. Other aspects of forest management, such as species composition and stand age, were not addressed with this approach (Schall and Ammer

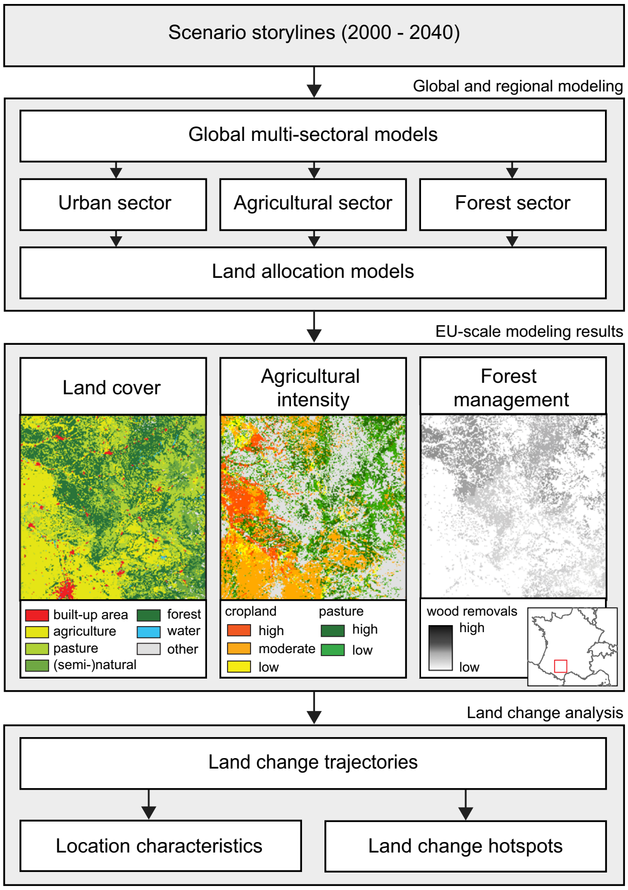

Fig. 1 Overview of modeling chain and analysis

2013). Wood removals (m^3/ha/year) were projected with EFISCEN on subnational level (Verkerk et al. 2014). We applied a disaggregation approach (Elbersen et al. 2012) using tree species maps (Brus et al. 2011), harvest likelihood maps (Verkerk et al. 2015), and forest cover maps as simulated for the scenarios by the Dyna-CLUE model. Wood removals were only available for time steps which covered the years 2010 onwards. We assumed wood removals to be constant between 2000 and 2010 and interpolated volumes of wood removals in 2010 for forest extent in 2000 (Fig. 1). Detailed information on the linked modeling system is found in Lotze-Campen et al. (in preparation for this issue) and in the Supplementary Material, Annex B.

Land change trajectories

We identified land change trajectories which (1) represent well-known and significant land change trends in Europe, (2) make optimal use of the simulation results of the available models, and (3) cover all possible land conversions on the grid level modeled with Dyna-CLUE (Table 2). An overview of all identified land change trajectories is found in Table 3. Each land change trajectory can be characterized by two dimensions: (1) The increasing or decreasing human impact a land change trajectory may have on the landscape and (2) the spatial extent of the landscape relevant to the trajectory, i.e., the role of landscape neighborhood on the locally identified land use change (Fig. 2). Within each scenario simulation, we assigned each pixel that was not stable over time to one or more land change trajectories according to classification rules of varying complexity (Fig. 3).

Most land change trajectories can be identified by consideration of local variables only, for example intensity changes and land cover conversions such as land abandonment. Other trajectories required additional information, for example urban and peri-urban growth. Here, in a first step, urban cores and peri-urban belts are delineated for the scenarios in 2040, and in a second step, growth of built-up areas is classified to urban or peri-urban growth based on these masks. For the identification of the trajectory expansion of wild areas, first, wild areas were defined and delineated for 2000 and scenarios in 2040. Both land abandonment and reduced wood removals in forests within expanding wild areas were considered as contributions to the expansion of wild areas. For the trajectory polarization of rural land, the conjoint occurrence of land abandonment and intensification of agriculture were identified. For this, we masked the land abandonment trajectory with a focal map representing areas with contracting agriculture and the cropland and pasture intensification trajectories with focal maps representing areas where, on average, management intensified. These steps were taken to make sure that the land abandonment and intensification grid cells found were representative for the changes in the considered regions and were not counteracted by other developments. A full description of procedures used to delineate land change trajectories from the modeling results is found in the supplementary material, Annex C.

The delineation of land change hotspots facilitates the identification of drastic change events and allows for factoring in regional conditions and processes to contextualize land changes. As such, the identification of hotspots is valuable for prioritization of land use planning and policies. We delineated hotspots of occurrence (top 10 % quantile) for each of the considered land change trajectories (Fig. 4). We chose a uniform moving window of 15-km radius for hotspot delineation. This extent was chosen to allow reflecting regional-scale land changes, without omitting too much spatial detail. First, we quantified the relative extent of a land change trajectory within the specified neighborhood. Upon a decrease in a particular land use, for example, through land abandonment, we then calculated the relative extent of agricultural land within each neighborhood in the reference year and used this value to weight the relative extent of land abandonment within the specified neighborhood.

Table 2 Land cover changes in Dyna-CLUE and associated land change trajectories delineated in this study

	Land cover in year 2040				
	Built-up	Cropland	Pasture	(Semi)Natural	Forest
Land cover in year 2000					
Built-up	Stability	–	–	–	–
Cropland	Urban growth Peri-urban growth	Stability De-intensification Intensification Polarization of rural land	Cropland to pasture	Land abandonment Polarization of rural land Expansion of wild areas	Land abandonment Polarization of rural land Expansion of wild areas
Pasture	Urban growth Peri-urban growth	Recultivation of pasture	Stability De-intensification Intensification Polarization of rural land	Land abandonment Polarization of rural land Expansion of wild areas	Land abandonment Polarization of rural land Expansion of wild areas
(Semi-)Natural	Urban growth Peri-urban growth Contraction of wild areas	Recultivation of green space Contraction of wild areas	Recultivation of green space Contraction of wild areas	Stability	Contraction of wild areas
Forest	Urban growth Peri-urban growth Contraction of wild areas	Recultivation of green space Contraction of wild areas	Recultivation of green space Contraction of wild areas	–	Stability De-intensification Intensification Contraction of wild areas

This leads to the accentuation of areas (1) where land abandonment occurs frequently within the specified neighborhood and (2) whose neighborhoods were dominated by agriculture in the reference year. To make sure we only considered neighborhoods where land abandonment was not offset by agricultural expansion, only grid cells with contracting agriculture cover in their neighborhoods are eligible for the hotspot delineation (Fig. 4). A full description of procedures used to delineate land change hotspots from the modeling results is found in the supplementary material, Annex C. We mapped all hotspots of land change trajectories per land use scenario (Fig. 8). As land change trajectories can overlap (for example, land abandonment and polarization of rural land), we implemented a visualization hierarchy based on Fig. 3 and gave mapping priority with increasing complexity and increasing human impact of a given land change trajectory.

Location characteristics of land change trajectories

We used six indicators which represent ecosystem service provision and other location characteristics to portray locations where particular land changes occur in the future scenarios (hereafter referred to as location characteristics). Doing so reveals the potential impact of a particular land change trajectory on an affected location and may indicate threats and benefits for human well-being. All indicators were available on a 1 km^2 grid across the EU and reflected the state around the year 2000.

Carbon sequestration

Carbon sequestration describes the uptake of atmospheric carbon dioxide in soil and biomass. Sequestration rates are region-specific and depend on land cover and land use, forest age, soil, and the amount of carbon which is already present in the soil. In this study, carbon sequestration was expressed as carbon stock changes per km^2 per year (Mg C km^{-2} $year^{-1}$) following Schulp et al. (2008).

Erosion risk

Soil erosion risk is a disservice that depends on land cover and land use, soil erodibility, topography, and rainfall regime. Here, the indicator developed by Pérez-Soba et al. (2010) was based on the Universal Soil Loss Equation (Wischmeyer and Smith 1978). Erosion risk is given in tons per hectare at a 1 km^2 resolution.

Nature-based tourism

Nature-based tourism addresses the capacity of the ecosystem to support recreation and tourism (e.g., winter

Table 3 Overview of land change trajectories and the rules used for detection

Land change trajectory name	Short description	Classification rules
Stability	No change in land cover nor land management intensity	Grid cells covered by a dynamic land cover category (built-up area, arable land (incl. permanent crops), pasture, (semi-)natural land, and forest) in the reference year, for which neither land cover nor management intensity changed in the scenarios
Intensification and de-intensification	Change in land management intensity	Increase or decrease of (a) fertilizer use on arable land (b) grazing intensity on pastures (c) wood removals in forests. All grid cells which had a higher (lower) intensity category than the reference year were considered intensifying (de-intensifying)
		Changes in wood removals of more than 25 % compared to the reference year were considered intensifying or de-intensifying
Expansion and decline	Land cover conversions	Land cover that converted to another land cover category on the grid level
Land abandonment	Conversion of agriculture to green space	Conversion of agriculture (i.e., arable land and pasture) in the reference year to green space (i.e., forest or (semi-)natural vegetation)
Arable land to pasture	Conversion of arable land to pasture	Conversion of arable land in the reference year to pasture
Recultivation of green space	Conversion of green space to agriculture	Grid cells covered by green space (i.e., forest or (semi-)natural vegetation) in the reference year converted into agriculture
Recultivation of pasture	Conversion of pasture to arable land	Grid cells covered by pasture in the reference year converted to arable land
Polarization of rural land	Parallel land abandonment and intensification in remaining agriculture patches	Grid cells which display land abandonment or agricultural intensification in regions where agricultural area declined and agricultural intensity increased within a radius of 15 km
Urban growth	Growth of built-up area which adds to an urban core	Expansion of built-up area was only identified as urban growth if it led to the expansion of an urban core in immediate adjacency. Urban cores were derived from DGUR (degree of urbanization typology) available from Eurostat (2001) and merged with the extent of built-up area in the reference year to distinguish urban agglomerations from other built-up areas
Peri-urban growth	Growth of built-up area located in the rural–urban fringe	New built-up area located within the expanding rural–urban fringe in a scenario was addressed as peri-urban growth. The rural–urban fringe was identified as the area between the outskirts of an urban agglomeration and the countryside. We varied the size of the rural–urban fringe with respect to the size of the urban cores by using a diameter of twice the radius of the urban core to delineate the extent of the rural–urban fringe. When an urban core expanded in a scenario, its associated rural–urban fringe expanded proportionally
Expansion of wild areas	Conversion of agriculture and intensively managed forest to a more natural vegetation cover, adding to contiguous patches of nature	Grid cells which contributed to the growth of wild areas were considered expansion of wild areas. Wild areas were defined as contiguous patches of nature larger than 1000 km^2 (Wild Europe 2013). Nature could comprise all land cover which was not covered by built-up area, agriculture, pasture, and intensively managed forest. Nature in adjacency to built-up area or agriculture was not considered eligible as a part of wild area. Only patches of wild area which showed net growth were considered
Contraction of wild areas	Conversion of wild areas to built-up area, agriculture or high intensity forest	Grid cells which were part of wild areas in the reference year and converted to built-up area, agriculture, or intensively managed forest during a scenario were considered as contraction of wild areas

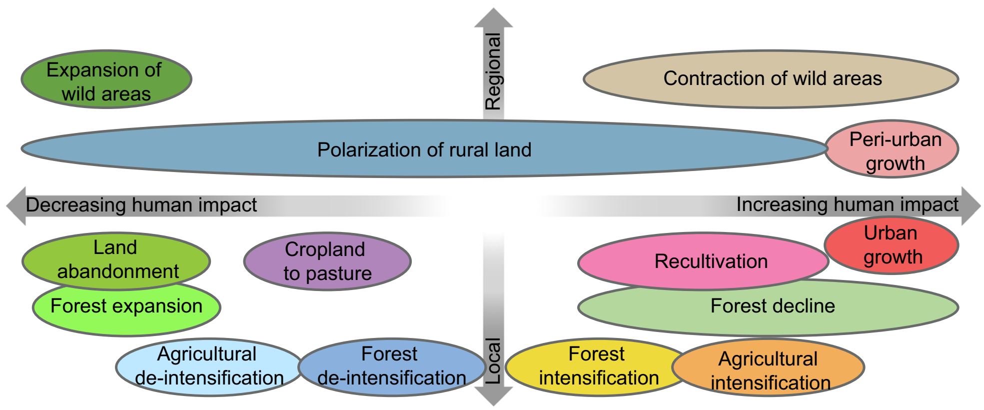

Fig. 2 Land change trajectories arranged according to the human impact on the landscape (*horizontal axis*) and the spatial range accounted for in their description (*vertical axis*)

sports, camping). In the mapping approach developed by van Berkel and Verburg (2011), suitability for nature-based tourism depends on landscape features such as relief, proximity to rivers, lakes and coasts, the presence of natural monuments, and high nature value farmland. This indicator was given as a dimensionless index. Data were provided by Tucker et al. (2013).

Pollination

Pollination is vital for flowering plants and is indispensable for agriculture. For a wide range of crops, bees and other insects are the most important biotic pollen vectors. Here, pollination was expressed as a flow and depended on assumptions on potential habitat (% area) in the vicinity of croplands calculated according to the method documented by Serna-Chavez et al. (2014) and provided by Tucker et al. (2013).

Maintenance of soil quality

Soil organic matter stock in the topsoil is a common proxy for the capacity of the ecosystem to maintain soil quality (Reeves 1997). Soil organic matter (Gg per km^2) estimates for the reference year were derived from Jones et al. (2004) and Jones et al. (2005) and provided by Tucker et al. (2013).

Flood regulation

Flood regulation is the capacity of land to mitigate and lower flood events by means of runoff reduction through retention and evapotranspiration. Its supply depends on the land cover and land use, soil conditions, and location factors. Flood regulation is given as a dimensionless index following Stürck et al. (2014).

We characterized locations subject to land use change by the location characteristics in the reference year. We hypothesized that the locations affected by different land change trajectories differ in their location characteristics. We tested whether location characteristics differed significantly for the different land change trajectories within one scenario using a Mann–Whitney *U* test. Significant differences indicated that different land change trajectories affected different locations. We subset particular trajectories (land abandonment to land abandonment only and expansion of wild areas, and polarization of rural land to land abandonment and intensification of cropland and pasture) and visualized location characteristics per land change trajectory across all land use scenarios using star plots. All analyses were conducted using R (R Development Core Team 2012).

Results

Land change trajectories

We quantified the occurrence of each land change trajectory per scenario (Fig. 5). To analyze the consistency of the occurrence of land change trajectories between scenarios, we overlaid particular land change trajectories in all scenarios and quantified their frequency of occurrence at each grid cell (Figs. 6, 7). We summarized hotspots of land change trajectories in Fig. 8. An overlay of particular land change trajectory hotspots in different scenarios is presented in Fig. 9. Overall, land change trajectories have largest extents in the "Libertarian Europe" (V-A1) and "Social Democracy Europe" (V-B1) scenarios. Grid cells which face change in all scenarios are particularly frequent in eastern Europe, while in western Europe, future changes are more diverse across scenarios and overlap less (Fig. 6).

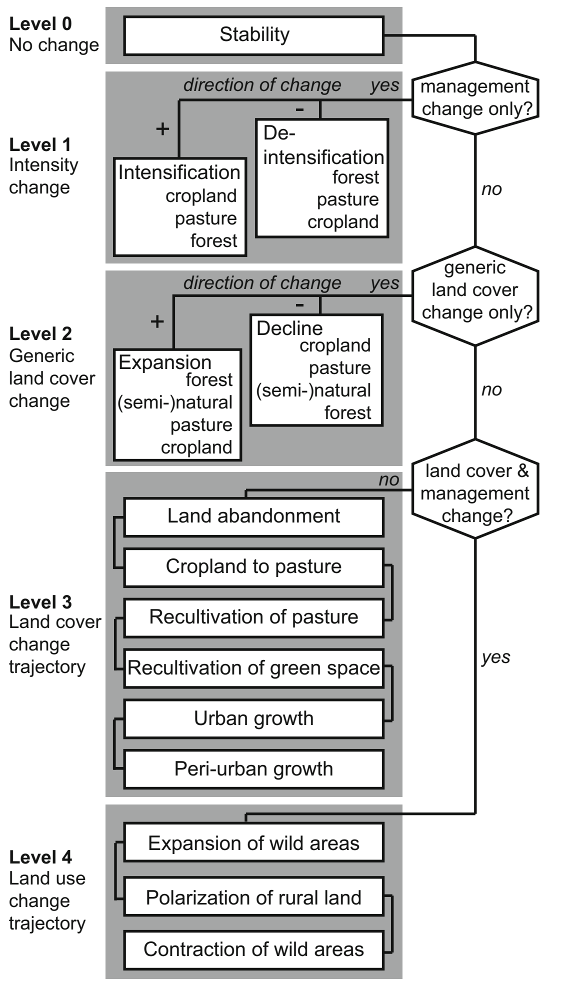

Fig. 3 Hierarchy of land change trajectories used in creation of land change hotspot maps

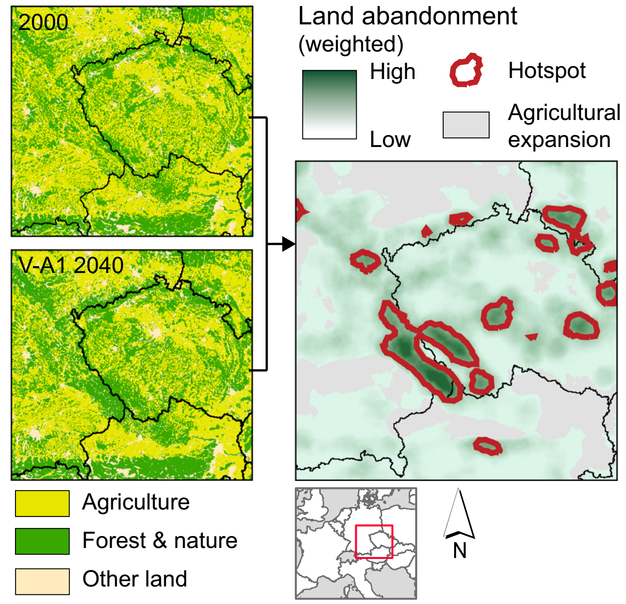

Fig. 4 Hotspot mapping approach, exemplified for the land change trajectory land abandonment

In the following section, we present characteristics of land change trajectories in the different land use scenarios.

In "Libertarian Europe" (V-A1), change affects particularly the agricultural sector. Land abandonment affects more than 170,000 km^2 of agricultural land. This development is accompanied by conversion of cropland to pasture and large areas of de-intensification trajectories (Fig. 5). V-A1 displays the largest extent of expansion of wild areas. Intensification of agricultural land predominately occurs within areas characterized by polarization of rural land. On the other hand, large extents of green space are recultivated to agricultural land (ca. 41,000 km^2).

Land abandonment hotspots are located particularly in eastern and southern Europe (Fig. 8). Agricultural landscapes in northern Italy, Poland, and Romania are affected by land abandonment in all scenarios (Fig. 9a), while hotspots in western Europe are more diverse between scenarios and most frequent under "Libertarian Europe" (V-A1) and "Social Democracy Europe" (V-B1). Land abandonment hotspots are often accompanied by expansion of wild areas, particularly in southern Europe. The conversion of cropland to pasture is a trajectory predominately found in Portugal, Spain, and the UK, and hotspots of de-intensification trajectories dominate as well in Portugal, the UK, and France. Hotspots of polarization of rural land are mostly confined to Poland, Hungary, and Romania.

In "Eurosceptic Europe" (V-A2), the agricultural sector follows a different development. Agriculture intensifies the most as compared to the other scenarios (Fig. 5). Land abandonment is less frequent than in V-A1, yet is not offset by recultivation of green space, resulting in a relative loss of agricultural area also in V-A2. Expansion of wild areas is less frequent than in V-A1, and hotspots are confined mostly to Alpine regions and Scandinavia. Extents of contraction of wild areas, on the other hand, are comparable to V-A1 and offset by expansion of wild areas within the EU.

In "Social Democracy Europe" (V-B1), changes in the agricultural sector are similar to V-A1. While land abandonment is on a similar level (173,000 km^2) and hotspots are situated in similar regions as in V-A1, expansion of wild areas is less abundant than in V-A1 and hotspots are less associated with land abandonment hotspots (Fig. 8). Also contraction of wild areas affects larger areas (19,000 km^2) than in V-A1 and V-A2 and is associated with forest intensification, for example, in Sweden (Fig. 8). Polarization of rural land is most frequent under V-B1 and is the only one with hotspots of polarization outside of eastern Europe, for example in northern France.

Agricultural change trajectories in "European Localism" (V-B2) are comparable to V-A2, for example, in

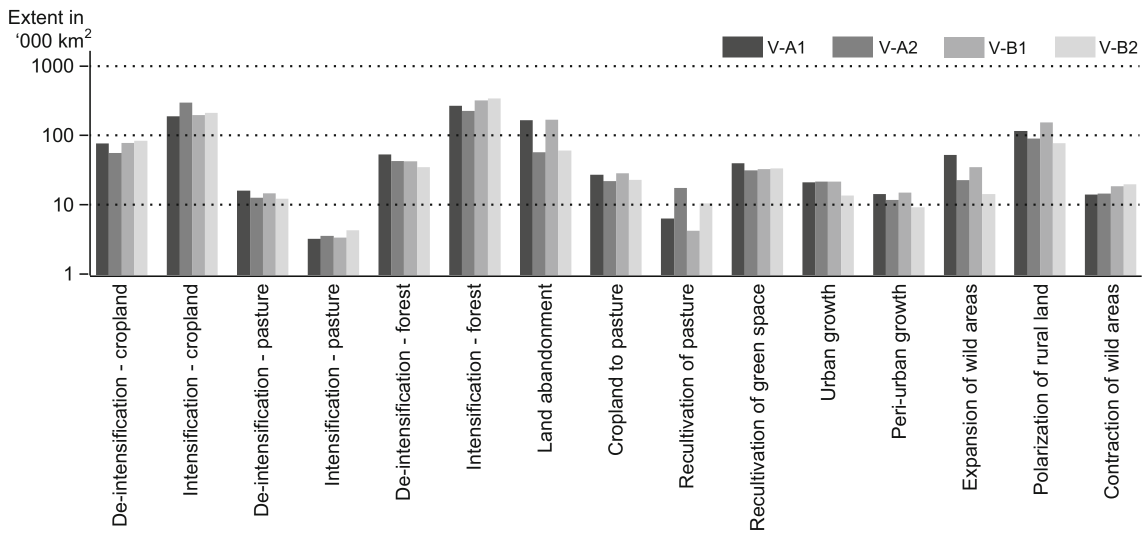

Fig. 5 Spatial occurrence of land change trajectories (in 1000 km^2) per scenario

terms of land abandonment and recultivation of pasture. In V-B2, the extent of expansion of wild areas is smallest across scenarios, with hotspots predominately located in Scandinavia and the Alps. V-B2 is the only scenario in which the trajectory contraction of wild areas covers larger extents than expansion of wild areas (20,000 and 15,000 km^2, respectively). While urban growth is comparatively high in the other scenarios (22,000 km^2), expansion of urban cores is smaller in V-B2 (14,000 km^2).

Land change trajectories are affected differently by the underlying scenario storylines. While, for example, grid cells which are affected by contraction of wild areas overlap to great extents between scenarios (Fig. 7f), other trajectories are more versatile, for example expansion of wild areas (Fig. 7c). Trajectory hotspots, in general, display less variability. In Fig. 9, scenario hotspots of (a) land abandonment, (b) polarization of rural land, and (c) expansion of wild areas were overlaid. Hotspots of land abandonment are comparatively stable in eastern and southern Europe and more scenario-dependent in western Europe (Fig. 9a). Hotspots of polarization of rural land, on the other hand, overlap less frequently, but, except for one exception (V-B1), all hotspots are situated in eastern Europe (Fig. 9b). Expansion of wild areas is comparatively stable in the Alps, but more scenario-dependent in the rest of the EU (Fig. 9c).

Location characteristics of land change trajectories in land use scenarios

Land change trajectories can be differentiated based on the composition of location characteristics in the reference year. Most location characteristics associated with a particular

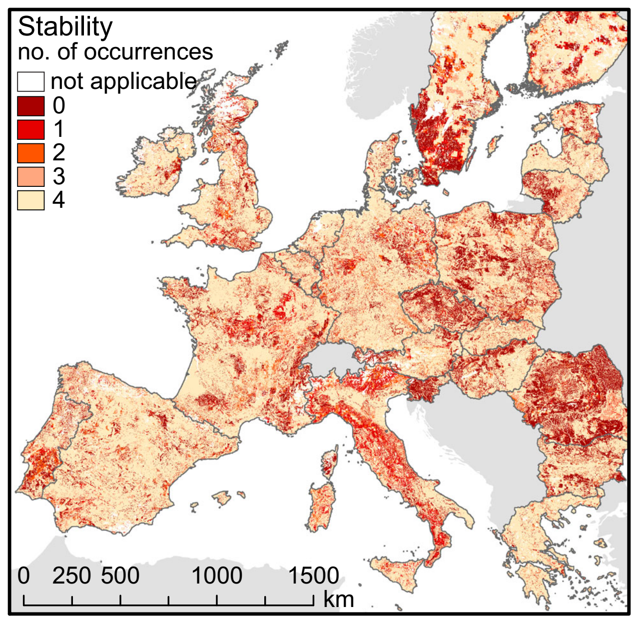

Fig. 6 Frequency of stability in the four scenarios

land change trajectory were similar across scenarios. Recultivation of pasture, cropland to pasture, and expansion of wild areas showed larger differences between scenarios (Fig. S7), particularly due to variations in carbon sequestration and erosion risk. Because of the similarity in location characteristics across scenarios, we exemplarily present the results for V-B1 here (Fig. 10). The results for the other scenarios are presented in Fig. S7 and Tables S3–S6.

Despite originating from similar land uses in the reference year, particular trajectories differ considerably in terms of their location characteristics, specifically with respect to carbon sequestration, pollination, maintenance of

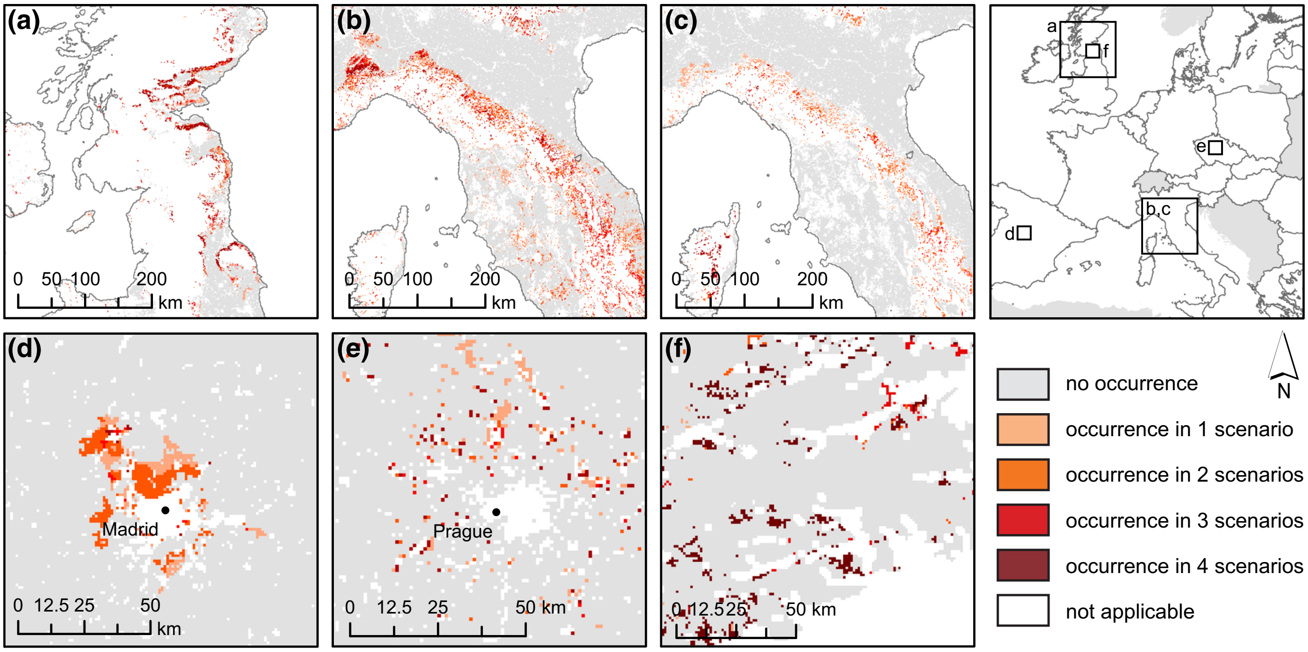

Fig. 7 Frequency of occurrence of land change trajectories in the four scenarios. **a** Cropland to pasture, **b** land abandonment, **c** expansion of wild areas, **d** urban growth, **e** peri-urban growth, **f** contraction of wild areas

soil quality, and flood regulation (p values <0.05, see Tables S7–S12). For example, location characteristics of intensifying forest grid cells differ from de-intensifying forest grid cells, cropland converted to pasture differs from cropland that intensifies toward 2040, and also the context of land abandonment (e.g., polarization of rural land, or expansion of wild areas) reveals significantly different location characteristics.

Locations characterized by intensification of forest management showed highest amounts of carbon sequestration, followed by locations subject to contraction of wild areas and recultivation of green space. In 2000, erosion risk was highest at locations affected by the trajectories cropland to pasture and land abandonment. Nature-based tourism was most pronounced at locations which faced either contraction or expansion of wild areas. Pollination was only quantified for cropland, and was highest for cropland facing conversion to pasture, and for cropland associated with polarization of rural land. Maintenance of soil quality was on average highest at locations of forest management intensification, or locations which faced either contraction or expansion of wild areas. Flood regulation was most dominant for the land change trajectory de-intensification of forest management, as well as pasture intensification and expansion of wild areas.

In general, the trajectories contraction of wild areas, expansion of wild areas, and intensification of forest management occurred at locations with the highest overall ecosystem service provision (Fig. 10 and Table S5).

Discussion

Identification of land change trajectories

We used a novel combination of models to address both intensity and area changes in multiple land use sectors and integrates these different dimensions of land use change by delineating typical land change trajectories. Based on a novel set of scenarios and a chain of simulation models that address both changes in land cover and land use intensity, we have provided an analysis of the spatial patterns of land use change that Europe may face in the coming decades. Rather than presenting the raw modeling results, we delineated and quantified typical land change trajectories of varying complexity while accounting for the regional context of land change that was often disregarded in previous studies (e.g., Navarro and Pereira 2012).

A strength of the approach is that the scenarios reflect the uncertainty in future developments of the driving factors of land use in Europe and show how these work out in on the mosaic of different land change trajectories across the EU territory. At the same time, the uncertainty in data and model structures is not represented in our results. Other studies have investigated the propagation of error and uncertainty in linked modeling systems as used in this study (Verburg et al. 2013; Dunford et al. 2014). The study of Verburg et al. (2013) indicates that although uncertainty is inherently large, robust spatial patterns of change are obtained. Unfortunately, the absence of sufficiently

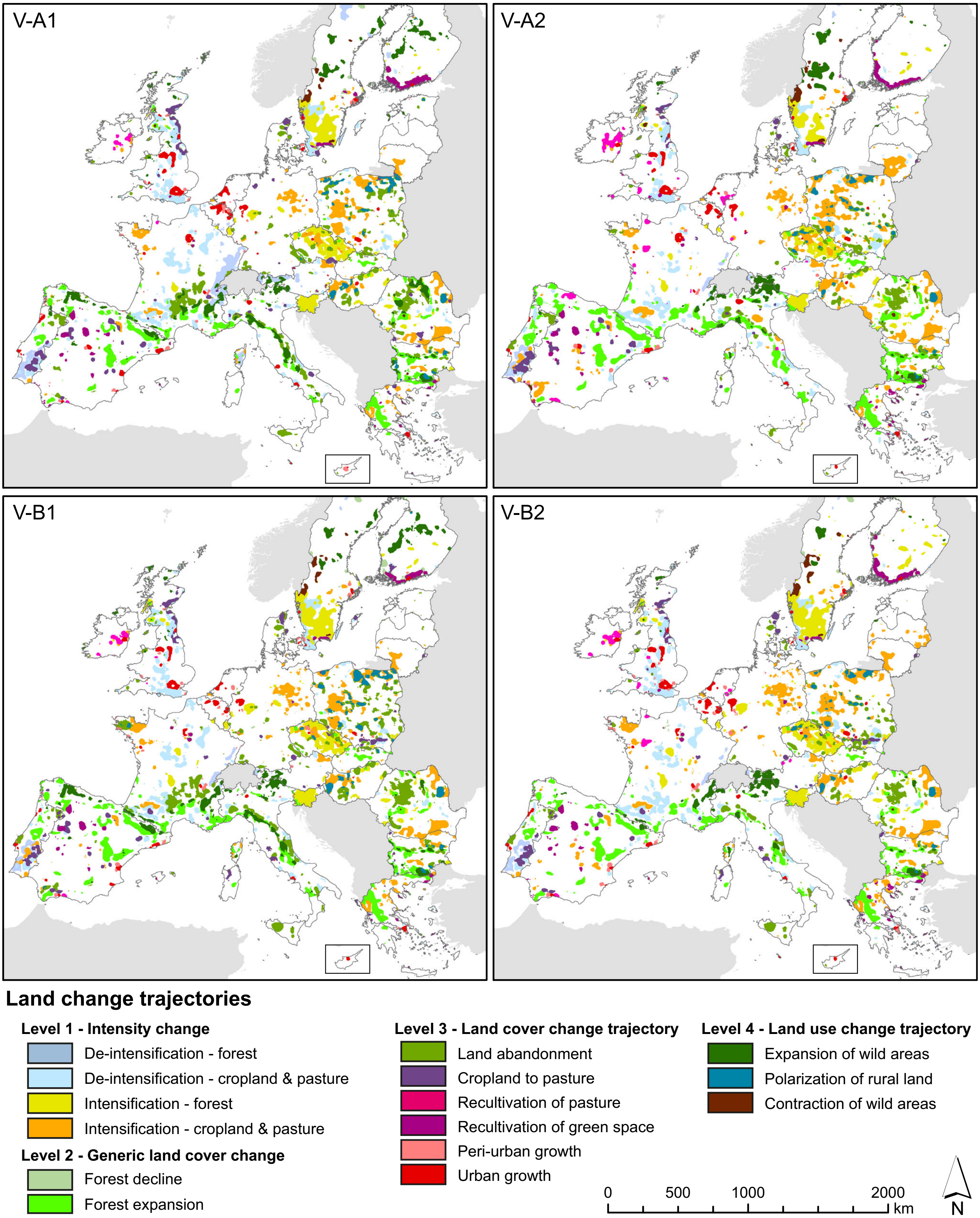

Fig. 8 Summary maps of land change trajectory hotspots per scenario

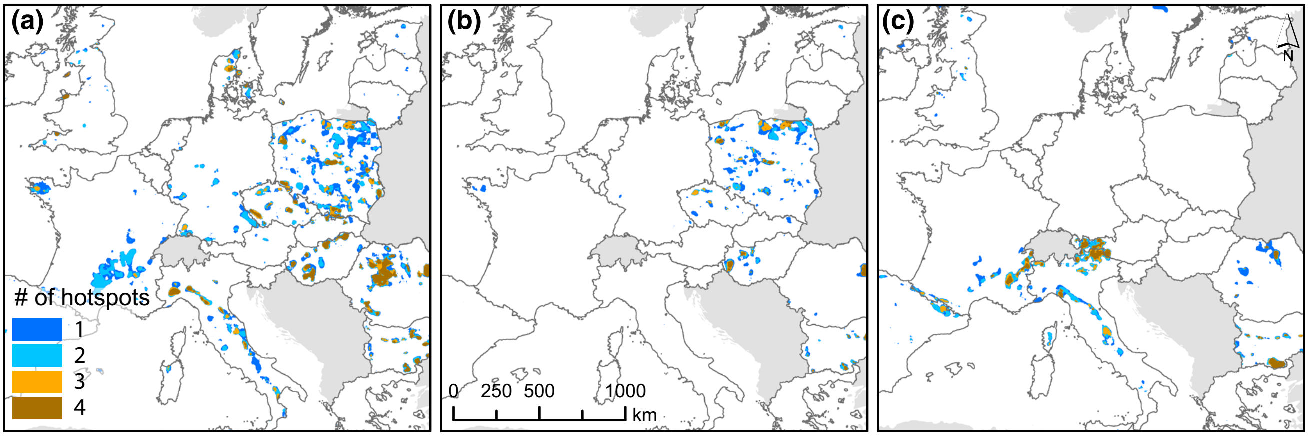

Fig. 9 Hotspot overlaps across the four scenarios for land change trajectories, **a** land abandonment, **b** polarization of rural land, and **c** expansion of wild areas

consistent change data for the European scale across longer time periods makes the validation of broad-scale land use models impossible.

The choice of land change trajectories in our study was largely determined by the information available from the underlying simulation models. This resulted in the trajectories to predominately reflect anthropogenic land use change in human-dominated landscapes such as agricultural, seminatural, or forest lands, while trajectories where the models did not provide sufficient information were not represented, for example glacier loss, or the conversion of wet- and peatlands. The approach contains the risk of oversimplification of complex land change trajectories. For example, the contribution of land abandonment to expansion of wild areas can be counteracted by the construction of roads that fragment large natural areas and impact the diversity and abundance of (native) species (Fahrig 2003). Yet, we ignored fragmentation through infrastructure development, as infrastructure expansion was not represented in the models. Other limitations of the approach relate to the sometimes arbitrary rules for defining the land change trajectories and the categorical inputs maps (e.g., management intensity levels). Moreover, while our analysis captures change within a particular region, some land change trajectories may have impacts elsewhere. For example, land abandonment can link to agricultural expansion in remote places (Fischer et al. 2014), which we are not able to trace with our approach.

Our hotspot maps help to visually access multiple complex change processes in one map and allow quantifying the consistency of severe changes across regions and scenarios. The hotspot maps contextualize grid level change within conditions and processes within their neighborhood. Assumptions on the considered neighborhood extent and thresholds to define a hotspot affect the delineation. However, there are no ecological processes that can be relied on to define a particular scale for consideration of a neighborhood. The neighborhood is chosen to be able to distinguish regional patterns by simultaneously reducing boundary effects common in analyses at the scale of administrative units or environmental zones. To test the sensitivity of the chosen approach, we recalculated the trajectory polarization of rural land for the V-B1 scenario with variable moving window sizes between 5 km and 50 km and quantified the consistency of the resulting hotspots by the degree of overlap (Fig. S2). Seventy-nine percentage of hotspot area based on a 5-km moving window lied within hotspots based on a 15-km moving window, and 84 % of hotspot area based on a 15-km moving window lied within hotspots based on a 50-km moving window, indicating a good agreement across scales and limited sensitivity to the chosen neighborhood size.

Hotspot definitions in the literature are ambiguous, and arbitrarily chosen cutoff values such as the 10 % quantile are commonly used for visualization or prioritization (e.g., Eigenbrod et al. 2010; Bai et al. 2011; Wu et al. 2013). The ambiguity of hotspot definitions necessitates clear documentation of the chosen hotspot delineation.

Analysis of land change trajectories and land change hotspots in Europe

Opposing trends in agricultural productivity across Europe were suggested by Audsley et al. (2006) as a result of climate change. Suitability for agriculture increases in northern Europe and decreases in the south. This process is reflected in our results: Recultivation is frequent in southern Finland and Sweden, while land abandonment is more widespread in Portugal and Italy. Particularly "Libertarian Europe" (V-A1) constitutes large changes in the agricultural sector: Liberalization of trade implies a strong

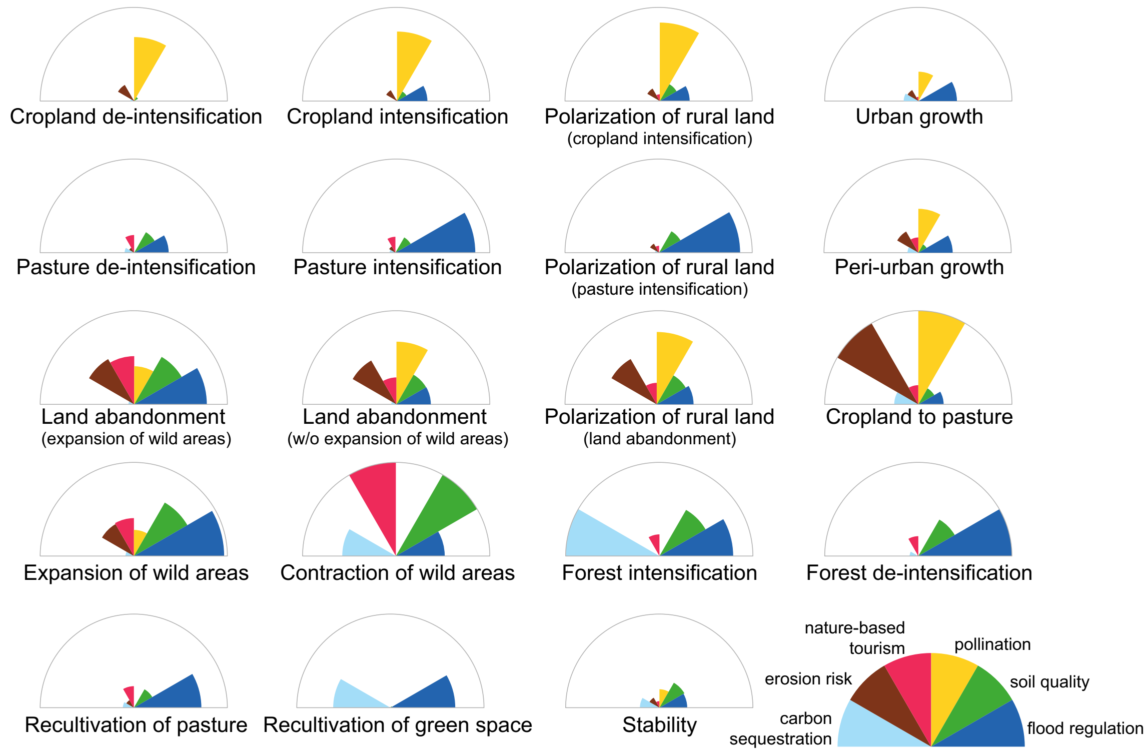

Fig. 10 Location characteristics associated with land change trajectories in scenario V-B1

orientation toward global markets and cuts of subsidies for European farmers. This development favors large-scale land abandonment, particularly in southern Europe. Land abandonment can have mixed outcomes. On the one hand, land abandonment can contribute to ecological restoration and increased carbon storage (Grau et al. 2004). On the other hand, land abandonment can result in reduced water availability (Rey Benayas 2007), higher wildfire risk (Moreira and Russo 2007), soil erosion (Stanchi et al. 2012), or the loss of agro-biodiversity and cultural landscapes (DLG 2005; Stoate et al. 2009; Fischer et al. 2012). Landscapes which face land abandonment and contraction of wild areas often feature high scenic and cultural heritage values. Changes in these landscapes can reduce the tourism and recreation functions leading to economic losses in local communities. Expansion of wild areas could therefore be a chance to maintain landscapes attractive for tourism and recreation.

All scenarios indicate that agricultural intensification and land abandonment frequently emerge within the same region in the form of polarization of rural land. Polarization of rural land is particularly frequent in “Social Democracy Europe” (V-B1) and most pronounced in eastern Europe (Figs. 5, 9b). These developments indicate substantial changes, socioeconomically and environmentally, for the affected regions (MacDonald et al. 2000; Cramer et al. 2008). The relationship between increasing agricultural productivity and declining agricultural areas resulting from abolished agricultural policy regulations is well in line with previous work (Rounsevell et al. 2006; Verburg et al. 2008; Renwick et al. 2013). However, the regional diversity in land change trajectories originating from these processes was not addressed previously.

The ecological footprint of European consumption outside of Europe is projected to increase drastically in V-A1, due to very little efforts to control land use change driven by agricultural expansion, but particularly due to increased food and feed demand compared to the reference year. Pasture extent in the EU, however, declines under all storylines, and modeled decreases in grazing intensity correspond well with other modeling studies as reviewed in Busch (2006), where these trends are explained by changes in animal feed (i.e., fodder crops instead of grazing) and shifts in meat preference (i.e., from beef to pork and poultry). Thus, land abandonment may lead to increased displacement of agricultural production to regions outside Europe, such as southeast Asia and South America (Meyfroidt et al. 2010; Kastner et al. 2011), which entails strong environmental trade-offs. Recultivation of abandoned farmland in the temperate zone has been suggested as an option to increase agricultural production within Europe, while mitigating some of the unwanted outcomes of land abandonment (Koning et al. 2008; Siebert et al. 2010; Johnston et al. 2011).

In “Eurosceptic Europe” (V-A2), a main policy theme impacting on the agricultural sector is European protectionism. Agricultural subsidies prevail, and trade regulations are installed (as opposed to V-A1 and V-B1). As a result, intensification of agriculture is high, and de-intensification processes are limited (as opposed to V-A1, where it is a European-wide trajectory). Expansion of wild areas is less frequent compared to V-A1 and V-B1. As a combined result of intensifying agricultural systems and weak regulation of land use change, wild areas contract (mostly in Finland, France, Greece, and Spain), and natural ecosystems are under strong pressure in this scenario. Contraction of wild areas, recultivation of green space, and intensification of forest management pose the largest threats for regulating and supporting services, such as carbon sequestration and maintenance of soil quality, under all storylines, as locations which face these land change trajectories feature currently highest ecosystem service provisioning.

In “European Localism” (V-B2), in contrast, de-intensification of agriculture is most frequent across scenarios, and intensification affects less agricultural area than in V-A2. In V-B2, agricultural area in the EU remains closest to the reference year. Accordingly, and despite stricter land use regulations compared to V-A2, expansion of wild areas is least frequent, and contraction of wild areas is not compensated for.

Forest cover increases considerably across all scenarios (2.9–3.7 % of total EU area), which is in line with observed reforestation trends over the last decades (Zanchi et al. 2007) and projections in previous scenario studies (Schröter et al. 2005; Rounsevell et al. 2006). Intensification of forest management is most frequent in Scandinavia and mountainous areas across Europe, even in the scenario projecting least intensification (V-A2). Regional declines of forest and seminatural land, but particularly intensification of forest management leads to the contraction of wild areas, particularly in Scotland and Scandinavia. Contracting wild areas overlap more among scenarios than locations subject to expansion of wild areas, which suggests a higher path dependency for this trajectory.

Despite a similar strong population growth, increases in the extent of built-up area are 3 % smaller in V-A2 as compared to V-A1 as a result of less economic growth. However, at the same time, urban areas grow stronger in V-A2 than in V-A1, while peri-urban growth is much less pronounced. This reflects an emphasis of compact urban growth in V-A2 as opposed to urban sprawl in V-A1 (Fig. 5).

Conclusions

The identification and visualization of land change trajectories provide a number of important insights into future land use in Europe. Some land change trajectories, particularly those related to land abandonment and agricultural intensification, are very variable across scenarios, due to different storylines with respect to agricultural subsidies and trade. At the same time, many hotspots of land change are found at similar locations across the scenarios, showing much less variation across scenarios as compared to the full spatial extent of the trajectories. This indicates a high likelihood for those regions, largely irrespective of future developments, to experience a particular type of land change. It also suggests that the large-scale policies and regulations assumed under the more regulated scenarios do not sufficiently counteract these anticipated changes. Therefore, these regions may require local adaptation strategies to deal with the land change pressures and opportunities in the next decades. The differences in the response of particular land change trajectories to scenario conditions thus require different policy and planning tools in order to steer them in desired directions. Likewise, a high spatial variation of different, sometimes contrasting, land change trajectories across the EU also reflects differences in the socioeconomic, environmental, and land use history across Europe.

Location characteristics are changing in the course of land change, which involves the risk of losing pivotal ecosystem services. We highlighted that locations affected by certain land change trajectories can be portrayed by a range of distinctive location characteristics such as ecosystem service provision in the reference year. Our results can support the discussion on replacement costs for ecosystem services (e.g., Winfree et al. 2011) and address how ecosystem service loss can be compensated for (e.g., Gardner et al. 2013; van Teeffelen et al. 2014). Our findings indicate the need for region-specific planning and policy making to guide land change to avoid negative impacts on environment and society.

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