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**PROJECT CONTEXT**

VOLANTE ([www.volante-project.eu](http://www.volante-project.eu)) seeks to provide an interdisciplinary scientific basis to inform land use and natural resource management policies and decision-making. This will be achieved by advancing knowledge in land system science and using this knowledge to develop a roadmap for future land resource management in Europe. VOLANTE establishes new methodologies and integrated models to analyze human-environment interactions, feedbacks in land use systems, hotspots of land use transitions and identify critical thresholds in land system dynamics. The roadmap will bring together the science-base that VOLANTE will establish with key players in research, policy, business and NGOs, and the roadmap will be a significant European Science Policy Briefing for the years to come in the promotion of multifunctional and sustainable pathways of land system change.

The Module PROCESSES in VOLANTE seeks to understand the socio-economic and ecological processes that shape land use transitions in Europe. This is addressed via studying land system dynamics and land use decision making across a range of spatial scales, from local case studies to all of Europe, and temporal scales, from recent to long-term changes in land systems. Within the module processes, Work Package 3 (WP3) focuses on recent land use change at the *pan-European scale*, by analyzing rates and patterns of land change, by detecting hotspots of land use change, by exploring what drives spatial patterns of land change, and by identifying archetypical combinations of drivers and outcomes in land systems. WP3 has a specific focus on exploring and understanding the rates and spatial patterns of changes in land use intensity.

This deliverable (D3.2) documents results of an assessment of hotspots of land system change across Europe, pertaining to changes in both area extent and management intensity, and considering forestry, cropland, grazing, urban area, and conservation lands. These identified maps of hotspots of land system change form the basis for subsequent analyses within WP3, including (a) the interpretation of change patterns, (b) the analyses of underlying drivers and spatial determinants of land use change, and (c) the identification of archetypical change pathways and patterns. The results from WP3 will furthermore inform assessments of changes in ecosystem service provision in WP8, and are foreseen to provide a basis for the interpretation of future scenarios in the pathway analyses in WP11.

Deliverable D3.2 is written in the style of a research paper to be submitted to a peer-reviewed, international journal once papers on individual land change processes that this paper...
depends on have been submitted, and once the interpretation of change patterns has been carried out. We therefore emphasize that this document should be seen as a discussion paper and progress report regarding the work on understanding broad-scale spatial patterns of land use change carried out in WP3. Submission of papers on individual land change indicators and processes are foreseen for 2013 and early 2014. A revised version of the manuscript resulting from D3.2 shown here will be submitted within the lifetime of VOLANTE.
This is a draft manuscript documenting the progress in Work Package 3. The final manuscript is contingent on the submission of a range of papers on individual land change processes as well as on the subsequent analyses of drivers of land use change in WP3. This document is therefore not a citable manuscript and we refer to the final version of this manuscript, which will be made available via the Volante website (www.volante-project.eu) once published.

Hotspots of land system change in Europe

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Introduction

Humankind crucially depends on the land-based production of food, fiber and bioenergy (Tilman et al., 2011, Erb et al., 2012). Land use, however, has substantial environmental trade-offs, including the degradation and loss of ecosystems and their biodiversity, as well as the services they provide to mankind (Foley et al., 2005, MA, 2005). Land use change is also a major driver of climate change and has altered major biogeochemical cycles. Clearly, the global land system is currently not in a sustainable mode, and understanding where and how land use changes is therefore important for identifying, managing, and mitigating the trade-offs of land-based production (Foley et al., 2011).

In the past, land change science has predominantly focused on understanding conversions in land cover, including deforestation (e.g., Geist and Lambin, 2002, Hansen et al., 2010), urbanization (e.g., Deng et al., 2008, Taubenböck et al., 2012), and forest expansion (e.g., Rudel et al., 2005, Meyfroidt and Lambin, 2011). In contrast, changes in the intensity of land use within a land cover category (e.g., agricultural intensification, changing grazing pressure) have received less attention (Erb et al., 2013). This is unfortunate because intensity changes are widespread and account for a major share of production increases over the last decades, particularly in industrialized countries (Rudel et al., 2009, Rounsevell et al., 2012). Although land conversions remain widespread in some world regions, intensification of existing cropping, grazing, and forestry systems increasingly becomes important to satisfy growing demands for land-based production, as most fertile lands are already in use and the conversion of remaining wildlands becomes less acceptable (Beringer et al., 2011, Lambin and Meyfroidt, 2011). Land use intensification is therefore likely a key strategy to help satisfy growing future demands for agricultural and forestry products (Godfray et al., 2010, Foley et al., 2011). At the same time, intensification, just like land conversions, entails substantial environmental trade-offs (e.g. greenhouse gas emissions, pollution of surface and groundwater by agrochemicals) (Stoate et al., 2001, Foley et al., 2005, Paillet et al., 2010), which may lead to a reduction in input intensity in areas where land use intensity has been high in recent history. Finally, higher land use intensity typically raises agricultural output per unit area and can therefore relax land use pressure elsewhere, leading to decreasing land use intensity, less land expansion, or abandonment (i.e., a land sparing effect, Ewers et al., 2009, Rudel et al., 2009). Assessing the net effect of intensification on ecosystem services and biodiversity is therefore challenging, and a better
understanding of the dynamics of land use intensity is therefore urgently needed. However, this is currently constrained by a lack of adequate datasets capturing land use intensity changes across larger areas (Verburg et al., 2011, Fritz et al., 2013, Kueемmerle et al., 2013).

Whereas pathways of land system change have frequently been depicted as unidirectional transitions along an intensification gradient, for example from subsistence to small-scale farming to capital-intensive, industrialized agriculture (DeFries et al., 2004), recent evidence suggests a more nuanced picture. Bi-directional trends of change may be frequent, with intensification occurring alongside abandonment (Mather, 1992, Stoate et al., 2009, Lambin and Meyfroidt, 2010, Piquer-Rodríguez et al., 2012). Globalization, through the integration of formerly remote regions into world markets, and urbanization are primary drivers of such a land use polarization, leading to a reorganization of land use systems (Aide and Grau, 2004, Lambin and Meyfroidt, 2011, Seto et al., 2012). Moreover, the conservation of land to protect ecosystems, non-provisioning ecosystem services (e.g., carbon sequestration and storage), and biodiversity has become a major land use practice globally (Jenkins and Joppa, 2009), potentially exerting feedbacks on agricultural lands and forestry. Overall, we know little about how the spatial patterns of area changes, intensification, and lessening land use intensity relate to each other, nor how changes in one sector (e.g., agriculture) relate to changes in another (e.g., forestry, urban areas, conservation lands).

Europe is an archetypical example of a region where land use systems have predominantly changed along intensification gradients during the last decades (Rounsevell et al., 2012). Agricultural systems were intensified substantially, especially during the 1960s to 80s, and Europe today has some of the most intensively managed croplands in the world (Fig. 1). On the other hand, agricultural area has declined as marginal farmland was abandoned, partly due to a declining profitability of farming in such areas and partly due to rural-urban migrations (MacDonald et al., 2000, Navarro and Pereira, 2012). This triggered the widespread loss of traditional, multifunctional landscapes (Fischer et al., 2012) and led to a substantial increase in forest area since the 1950’s (Leip et al., 2008, Fuchs et al., 2012). Europe’s forests experienced a substantial increase in growing stock and increment levels, due to improved forest management, changes in age-class structure, site recovery after litter raking, as well as fertilization effects from nitrogen deposition and CO₂ enrichment (Leip et al., 2008, Bellassen et al., 2011, Vilén et al., 2012). At the same time, wood removals have also increased, albeit at a slower rate than the increment (Kuusela, 1994a, MacKenzie et al., 2006). Finally, Europe substantially expanded its
conservation network (Jones-Walters and Čivić, 2013), and concerns about the environmental trade-offs of intensification have resulted in a growing emphasis on fostering multifunctional landscapes through agri-environmental and set-aside schemes (Whittingham, 2011).

Where these different land change processes occur, and how their spatial patterns relate, however, is very poorly understood. Only a few studies have observed land use/cover conversions at the pan-European scale, either relying on non-representative samples of case study regions (Gerard et al., 2010) or the Coordinated Information on the European Environment (CORINE) land cover product (Kuusela, 1994a, Büttner et al., 2004, Feranec et al., 2007, Hatna and Bakker, 2011, Fuchs et al., 2012). While CORINE captures changes in broad land cover classes relatively well (e.g., urbanization), some key processes, for example farmland abandonment, are hard to identify based on single-date satellite imagery and CORINE estimates are therefore highly uncertain. Moreover, some cover changes do not entail changes in land use (e.g., forest cover via forest harvesting) or stability in land cover does not necessarily mean that land use remains stable (e.g., expansion of grazing into natural grasslands). Finally, rates and patterns of changes in the intensity of agriculture and forestry are not captured by CORINE and remain therefore weakly understood (Stoate et al., 2009). New datasets on land conversions and intensity changes have recently become available (Neumann et al., 2009, Temme and Verburg, 2011, Estel et al., in prep.; Plutzar, et al., in prep.; Verkerk et al., in prep., Overmars et al., 2013), providing new opportunities to better understand the relationship among different land change processes and the relative importance of area changes and intensity changes in Europe’s land systems.

This paper aims to provide a step towards a more complete representation of land system changes in Europe in terms of area changes and intensity changes in agriculture, forestry, urban areas, and conservation lands. Here, we assess the spatial pattern of key land system changes in Europe addressing not only land cover but also land management aspects. Specifically, we asked the following research questions:

1. Where are hotspots of key land system changes pertaining to agriculture, forestry, urbanization and nature conservation in Europe?

2. What is the importance of changes among broad land use classes relative to changes in the intensity within these classes?
3. How do spatial patterns of different land system changes relate to each other and which processes tend to co-occur?

Methods and Materials

Datasets used

Our study region was the EU-27 without Cyprus and Malta. We gathered data on changes in the extent and intensity of agriculture, grazing, and forestry, as well as information on changes in the extent of urban areas and conservation lands (Table 1). We obtained data at two different scales: (1) for administrative regions roughly representing the Nomenclature of territorial units (NUTS) 2 level (i.e., province level), and (2) in a grid level (with data aggregated or disaggregated to 1-km gridcells, see below). Data were collected for the time periods 1990-2000-2006/2010, or at higher temporal resolution depending on data availability. These datasets were then used to derive annual rates of change for these time periods.

To capture cropland area change we used two indicators: (1) cropland area and (2) area of permanent crops (e.g., fruit and olive orchards, vineyards). Cropland area at the NUTS-2 level was taken from the Common Agricultural Policy Regionalized Impact (CAPRI) database (Gimenez et al., 2012) for the years 1990, 2000, and 2006 (i.e., corresponding with the CORINE time cuts). Cropland here refers to arable land including fodder crops, but excluding permanent crops. At the grid level, we used the CAPRI-DynaSpat layers at a spatial resolution of 1 km² (Leip et al., 2008, Heckelei and Kempen, 2011), which provides cropland shares per gridcell and is consistent with the NUTS-2 CAPRI layers for the year 2000. We adjusted the DynaSpat layers to the different CORINE time cuts by constraining them to the extent of the higher resolution CORINE cropland mask, which included all agricultural areas except pastures. To do so, we discarded areas designated as cropland in DynaSpat, but not in CORINE, and used a simple nearest neighbor filling algorithm (each empty cell was assigned to the nearest class) where CORINE reported cropland but DynaSpat did not. For some countries CORINE coverage was not available for all three target years, and we used the cropland mask from preceding or subsequent time cuts in such cases. To ensure consistency between the CAPRI (NUTS-2) and gridded
cropland maps, we allocated the CAPRI cropland area to the grid level within a NUTS-2 region using the cropland fraction of the grid cells as weights (for details see Plutzar et al., in prep).

Pasture areas were processed in a similar fashion. We used total pasture area at the NUTS-2 level from the CAPRI database. To translate these to spatial patterns, we allocated grazing area numbers using the CORINE pasture class filling all available areas. Numbers that could not be allocated due to too little available space were allocated using the CORINE heterogeneous agricultural area class, as well as shrublands and herbaceous vegetation not designated as pastures. Finally, we merged the gridded pasture maps of both approaches into a single pasture map per time cut.

Farmland abandonment is poorly captured by CORINE (Verburg et al., 2009), and we, therefore, derived a farmland abandonment map from MODIS Normalized Differenced Vegetation Index (NDVI) time series from 2000 to 2012 at a spatial grain of 250m (Estel et al., in prep.). For each year of the time series, each gridcell within the CORINE agricultural classes (i.e., non-irrigated arable land, permanently irrigated land, rice fields, pastures, natural grasslands, and land principally occupied by agriculture, with significant areas of natural vegetation) was classified as active or fallow. Training and independent validation data for these analyses were derived from the Land Use/Cover Area Frame Statistical Survey (LUCAS, www.lucas-europa.info) as well as from jointly interpreting high-resolution images available in GoogleEarth and the yearly MODIS phenology profiles. The resulting annual active/fallow maps had overall accuracies between 78% and 90% (Estel et al., in prep.). Using the active/fallow time series, we defined four classes (1) permanent agriculture (max. 1x fallow in 2000-2012), (2) permanent unmanaged (max. 1x active in 2000-2012), (3) agricultural abandonment (max. 2x fallow in 2000-2004 and max. 1x active in 2008-2012), (4) recultivation (max. 1x active in 2000-2004 and max. 2x fallow in 2008-2012), and (5) complex cultivation patterns (all other active/fallow combinations). We then summarized unmanaged land and agricultural abandonment classes at NUTS-2 level (rate of abandoned or unmanaged land relative to all agricultural land) and at the 1-km grid level.

Assessing changes in forestland is challenging based on land cover maps such as CORINE, because most changes in forest cover relate to natural disturbance (e.g., storm or fire) or management (e.g., logging), but do not reflect changes in land use. To derive forest area maps at the NUTS-2 and grid levels, we therefore disaggregated country-level forestland statistics from Forest Europe et al. (2011), which provides details on the status of European forest systems. We
used data for the years 1990, 2000 and 2005 (i.e., consistent with the CORINE time cuts) and
disaggregated the country-level forest area to the regional level using dasymetric mapping with
regional forest area data collected from various national sources as ancillary information
(Verkerk et al., in prep). We then disaggregated regional level data to the 1-km grid level using
the spatial pattern of forests in CORINE (using layers from preceding or subsequent time cut in
case of countries with missing data). We used the same procedure to disaggregate country-level
data on the extent of other wooded land from Forest Europe (2011) and added them to the forest
land class at the regional and at the grid level.

To calculate the extent of urban area change, we relied on the 1990, 2000, and 2006
CORINE maps and calculated percent urban land cover within 1 km² cells based on the 11 urban
or built-up classes represented in the CORINE catalogue, following the change protocol
suggested by Feranec et al. (1994b). Regarding conservation lands, we used the Natura2000
layer, which includes protected areas designated under the Habitats Directive (Council Directive
well as the Common Database on Designated Areas (CDDA Version 10) which includes national
protected areas. Both datasets were provided by the European Environment Agency
(www.eea.europa.eu/data-and-maps/data/natura-2/). We used protected areas with the
International Union for the Conservation of Nature (IUCN) categories I to V. To assess the
expansion of conservation lands in Europe, we summarized newly established protected areas for
the time periods 1990-2000, 2000-2006, and 2006-2010, relying on the date when the site was
established (i.e., proposed as eligible for identification as a Site of Community Importance) or, if
this information was unavailable, on the confirmation or designation date. Dates were available
for 25,612 protected areas (i.e., 97%) in Europe and the remaining protected areas were
discarded.

To assess land use intensity, we followed the framework by Erb et al. (2013), which argues
that due to the multidimensionality of land use intensity, three complementary types of metrics
are required to adequately address land use intensity in a systemic way: (1) input metrics, which
measure the intensity of land use along input dimensions (e.g., fertilizer, cropping frequency,
rotation lengths); (2) output metrics, which relate outputs to inputs (e.g. yields, capital
productivity, or felling-to-increment ratios in forestry), and (3) system metrics, which relate the
inputs or outputs of land-based production to system properties (e.g., yield gaps (actual vs.
potential yield), or human appropriation of net primary production (HANPP).
In terms of cropland intensity, we gathered homogenized fertilizer use data at the NUTS-2 level. Regionalized time series of fertilizer data are not readily available and we therefore used the CAPRI database, which contains both manure and chemical fertilizer input for all major crops for 1990 – 2007. The CAPRI data were estimated using annual, national-level purchased mineral fertilizers (N, P$_2$O$_5$ and K$_2$O) per crop from the International Fertilizer Association and the European Fertilizer Manufacturers Association and Bayesian Highest Posterior Density (HPD) approach to fill data gaps while ensuring consistency between fertilizer supply and demand at the national and regional level. Moreover, consistency between different levels of aggregation should also be ensured. Manure availability was based on animal heads and conversion factors per animal type (see Creel and Creel, 2009 for details). To summarize the fertilizer data across different crop types we classified the cropland area of each NUTS-2 region into three fertilizer input classes: low (<50 kg/ha), medium (50-150 kg/ha) and high (>150 kg/ha) (Overmars et al., 2013). To downscale these fertilizer time series to the 1-km grid, we fitted multinomial regression models to predict probability maps for the three intensity classes. We used about 150,000 cropland points from the LUCAS database, assigned crop-specific nitrogen application rates, and used this dataset as response variable. As predictors, we used a set of environmental (i.e., soil, topography, climate) and socio-economic (i.e., population density and accessibility) factors (Temme and Verburg, 2011, Overmars et al., 2013). Regression models were estimated for each country separately, using regressions from neighboring countries for the few countries without LUCAS coverage. We then used a hierarchical procedure to allocate the total areas of the three fertilizer application classes at the NUTS-2 level to the 1-km grid level: we first allocated the highest intensity class, then least intensive class, and the remainder was allocated to the medium intensity class (Overmars et al., 2013). In the analysis we kept the cropland mask fixed at the year 2000 for reasons of simplicity.

In terms of cropland output intensity, we used yield data for the 13 most important crops in the EU (i.e., cereals, oilseeds, pulses, roots & tubers, sugar beet, olives, flax & hemp, wine & grapes, fruits, rice and vegetables). Yield data were taken from the CAPRI database at the NUTS-2 level for the time periods 1990, 2000 and 2006. To disaggregate the yield data to the 1-km grid level, we derived weights for cropland areas by calculating suitability maps for each crop type. These suitability maps were prepared using a maximum entropy algorithm (Phillips et al., 2006, You and Wood, 2006) using the LUCAS point data on crop occurrence and five bioclimatic variables (Hijmans et al., 2005), three soil variables (Ťupek et al., 2010), and a ruggedness index.
(Riley et al., 1999) as predictors (see Plutzar et al., in prep. for details). As an additional output intensity metric, we calculated labor productivity. To do so, we obtained NUTS-3 level data on the combined workforce in agriculture, forestry, and fisheries from Eurostat (www.eurostat.eu). We related workforce numbers for 1990, 2000, and 2006 to production output levels as estimated through the harvested biomass (NPPh, see HANPP section below) from the same years, as this conveniently expresses production levels in a measure comparable across sectors. Maps were created at NUTS-3 level. Workforce statistics for individual sector were not available.

Regarding grazing systems, we used two output metrics. First, we used animal numbers on ruminants (cattle, sheep and goats), X, and X at the NUTS-2 level from the CAPRI database for the years 1990, 2000, and 2006. Second, we used biomass yields (i.e., biomass removed from pastures) from the CAPRI data at the NUTS-2 level. For disaggregating the regional-level biomass yield data to the 1-km grid level, we used dasymetric mapping using index maps based on a combination of actual NPP for the three time cuts and slope as ancillary data. Slope was treated similar to Neumann et al. (2009), assuming a linear decrease of pasture suitability between 6% and 24%.

Second we derived grazing intensity on pasture land by downscaling the NUTS-2 level livestock numbers to 1-km grid level following a slightly adapted version of the method of Neumann et al. (2009). Resulting livestock densities on grassland were regarded as a proxy for the intensity of grassland use. The NUTS-2 level statistics do not distinguish between grazing and stall feeding. For the purpose of this indicator it was assumed that all dairy cattle, beef cattle, heifers, sheep and goats were dominantly grazing. We converted all livestock numbers to equivalent livestock units using region-dependent conversion factors. We then used a grazing potential map, using grassland productivity, terrain and accessibility as main determinants (documented and validated by Neumann et al. (2009)), to spatially allocate these livestock units. Areas with very low grazing potential were not allocated any livestock. Based on the resulting livestock densities four grazing intensity categories for grassland areas were distinguished (1: <25 LSU/km²; 2: 25-50 LSU/km²; 3: 50-100 LSU/km²; 4: >100 LSU/km²).

While several measures of forestry intensity have been suggested (Nabuurs et al., 2007, Luyssaert et al., 2011), there is a general lack of gridded forestry intensity dataset covering larger areas in Europe or elsewhere (FAOSTAT, 2013, Kuemmerle et al., 2013). As a result, we did not identify a dataset useful for generating an input intensity metric for forestry at the temporal and spatial scales we targeted here. In terms of output intensity, we used three metrics. First, we used
recently developed harvesting volume maps (Levers et al., in prep., Verkerk et al., in prep.),
based on annual regional-level wood harvest volume statistics from 2000 to 2010 for every
country in our study region. Statistics were harmonized to match national level harvest statistics
from Forest Europe et al. (2011). Based on a statistical analyses of the relationship of harvesting
patterns and a comprehensive set of biophysical and socioeconomic explanatory variables (see
Levers et al., in prep. for details) we disaggregated regional harvesting statistics to produce high-
resolution (1-km) wood harvest maps for our study region (see Verkerk et al., in prep. for details).
To extend the time period covered by the harvest volume statistics to 1990, our earliest time cut,
we disaggregated national-level harvesting data from Forest Europe et al. (2011) assuming
constant harvesting ratios among regions within a country (this assumption was supported by the
very stable harvesting patterns found by Levers et al., in prep.) and using the three forest area
maps developed above for consistency reasons.
Second, we converted harvested volume to harvest intensity. Harvested volume is not a
direct measure of forestry intensity, as harvest volume is to a large extent determined by the
typical productivity of forests, which differs greatly across Europe. Harvest intensity is therefore
typically expressed in relation to the increment (Forest Europe et al. 2011) and we therefore
converted our regional level harvesting maps to harvesting intensity maps using data on regional
increment estimates collected from various national sources (for details, see Verkerk et al. in
prep). This harvesting intensity indicator is not meaningful at high spatial resolution and we
therefore calculated it only at the NUTS-3 level, and only for 2000, 2006 and 2010 due to
missing increment data for 1990. As a third measure of forestry intensity, we used the combined
labor force in agriculture and forestry described above.
Regarding system level metrics for the land system as a whole, we used Human
Appropriation of Net Primary Production (HANPP, Haberl et al., 2007). To derive HANPP, we
calculated three items: potential Net Primary Production \( (\text{NPP}_{\text{orig-veg}}) \), actual NPP \( (\text{NPP}_{\text{act}}) \), and
harvested NPP \( (\text{HANPP}_{\text{harv}}) \). HANPP then is the difference between \( \text{NPP}_{\text{orig-veg}} \) and the sum of
\( \text{HANPP}_{\text{harv}} \) and \( \text{HANPP}_{\text{luc}} \), which is the difference between \( \text{NPP}_{\text{orig-veg}} \) and \( \text{NPP}_{\text{act}} \). We calculated
these items separately for six broad land use classes (cropland, forestry, grazing land, built-up
and infrastructure, non-productive and wetlands, and wilderness) by reconciling the spatial
pattern (1km) with census data (NUTS-2 or national level) on area covered by these classes and
carbon flows associated to them. To estimate \( \text{NPP}_{\text{orig-veg}} \), we used the LPJml dynamic vegetation
model. \( \text{HANPP}_{\text{harv}} \) was derived from area and harvesting statistics, mostly at NUTS-2 level and
disaggregated to 1km gridcells (see sections above). On cropland $NPP_{act}$ was extrapolated from $HANPP_{harv}$. For forests, $NPP_{act}$ was assumed to equal $NPP_{orig-veg}$. On grazing land, $NPP_{act}$ was assumed to equal $NPP_{orig-veg}$ on natural grasslands, and 0.8 times $NPP_{orig-veg}$ on artificial grazing lands (e.g., cleared forests). A detailed description of the HANPP calculations carried out is provided in Plutzar et al., (in prep.).

In addition to HANPP, we also used changes in realized rotation length as a system-level metric for forest systems. Rotation lengths were estimated using the European Forest Information SCENario model (Schelhaas et al., 2007), which is a large-scale forest resource model. In EFISCEN, the state of the forest is described as an area distribution over age- and volume-classes, based on forest inventory data. In the model, forest management actions are described via basic management regimes (which define the period when thinnings can take place and the minimum age for final fellings) and the demand for wood. Both the demand for wood and the management regimes determine the realized rotation lengths: if wood demand is high, realized rotation lengths are close to the specified minimum age for final fellings. Conversely, if wood demand is low, realized rotation lengths are longer. In this study, we used forest inventory data from Ťupek et al. (2010), tree-species specific rotation lengths from Nabuurs et al. (2007) and wood demand from FAOSTAT (2013). Rotation lengths were estimated for the years 1990, 2000 and 2010.

**Mapping hotspots of land system change**

Using the database of area and intensity changes described above, we calculated mean annual change rates for the time periods were data were available (1990-2000, 2000-2006, and 1990-2006 for most datasets). To map hotspots of land system change in Europe, we used the resulting annual rate of change maps for two analyses. First, we derived hotspots of change at the NUTS-2 level for each indicator separately. To do so, we calculated the upper and the lower 10% quantile of distribution of all positive values (indicating an increase in area or intensity) and the distribution of negative values (indicating a decrease in area or intensity). We labeled the lower 10% quantile of negative change rates as ‘hotspots of decrease’, the upper 10% of the positive change rates as ‘hotspots of increase’, and the combined upper 10% quantile of negative rates and the lower 10% quantile of positive rates as ‘coldspots’ (i.e., stable areas). At the grid level, we did the same analyses using 5% as the cut-off value.
Second, we overlaid all resulting hotspot maps on NUTS-2 level, differing between decreasing and increasing trends to summarize positive and negative overall change trends regarding area as well as intensity change. To do so, we summed up the number of positive and negative hotspots identified in the individual analyses for every NUTS-2 region to identify ‘hotspots of hotspots’, i.e., regions where many land change processes co-occur at high intensity.

**Results**

Our analyses of land system change at two spatial scales (NUTS-2 level and –km grid level) revealed diverse spatial patterns of change and stability across Europe. In the following, we first discuss the results concerning changes in the area of broad land use classes, before we proceed to discussing changes in the intensity of land use within broad land use categories. Finally, we assess the co-occurrence or spatial separation of different land change processes.

*Area changes among broad categories of land use*

In terms of conversions among broad land use types, the most widespread land use change between 1990 and 2006 was cropland decline (~130,400 km²), followed by forest area expansion (~70,300 km²), and pasture area increase (~66,300 km²), whereas the least common conversions among broad land use categories were permanent cropland decline (~17,000 km²) and urban expansion (~45,700 km²). At the pan-European scale, land conversion rates were overall moderate, ranging from <1% (changes in grazing land) to 5% (urban expansion). Land conversion rates did also not differ substantially among time periods (i.e., 1990-2000 vs. 2000-2006). The identified hotspots of land use conversions and stability were overall consistent among the two analyses, at the NUTS-2 level (Fig. 2) and the 1-km grid level (Fig. 3), that we carried out, despite partly different data sources and independent hotpots mapping.

<< FIGURE 2 >>

Hotspots of cropland decline at the NUTS-2 level were mainly located in Eastern Europe (e.g., eastern and southern Poland, central Romania, Bulgaria) and the Mediterranean (e.g., northern Spain, southern Italy; Fig. 2), with annual rates of up to 1.04%. Moreover, almost all NUTS regions in Europe exhibited declining cropland trends in both time periods (1990-2000 and 2000-2006), albeit the rates of decline were generally small. Hotspots of cropland decline at the grid level (Fig. 3) generally resembled those at the NUTS-2 level, but the grid-level analyses provided deeper insights into the spatial patterns of these declines (e.g., spatial patterns of
cropland decline in Poland’s northeast and southeast, or in Central Italy and on Sardinia). Only a few areas were characterized by cropland expansion, most notably hotspots in the Netherlands, Northern Germany, Central France, and the British Isles, albeit all at very small annual change rates (e.g., 0.47% in Antwerpen (Belgium), 0.38% in Weser-Ems (Germany) or 0.34% in Border, Midlands and Western (Ireland)). In contrast, large areas in Western and Central Europe were characterized as coldspots of cropland change (i.e., indicating stability), particularly in much of Germany, France, Spain, the Netherlands, and Denmark (Fig. 3).

Hotspots of decline in permanent crops (e.g., olive and fruit orchards, vineyards) occurred dominantly in the Mediterranean (Fig. 2). Comparison among NUTS-2 and grid-level hotspots revealed that most of these declines occurred in coastal areas, particularly on the western shore of Italy and the Mediterranean coastal areas of Spain (Fig. 3). Moreover, the cross-scale comparison showed that some hotspots of permanent cropland decline (i.e., high rates of decline) occurred in areas with very little permanent crop area (e.g., Scotland). The expansion of permanent crop area was overall relatively rare, with a few hotspots in Central and Southern Spain (e.g., Comunidad de Madrid), southern France (e.g., Midi-Pyrénées) and Greece (Fig. 3).

Hotspots of expansion of grazing land mainly occurred in eastern Europe (e.g., Southern and Central Poland, Central Romania) and the Iberian Peninsula (e.g., Central Spain, Southern Portugal; Fig. 2, Fig. 3). These areas generally corresponded well with areas of cropland decline (Fig. 3). Pasture decline mainly occurred in Ireland, Scotland, the Netherlands, the Pyrenees, as well as in some Central European regions (e.g., Slovenia, Northern Italy). Although most areas in Europe where characterized by slight declines in pasture areas (Fig. 2), thee declines were only moderate and our grid-level analyses showed that pastures in Europe stayed overall stable, particularly in Western and Central Europe (Fig. 3).

The MODIS satellite NDVI time series analyses suggested that in total 25,920 km² were abandoned (defined here as a transition from managed to unmanaged farmland). Hotspots of abandonment occurred predominantly in the Alps and in Northern Europe (i.e., Sweden and the Baltic States), whereas abandonment rates were relatively low in Western Europe (e.g., France, Germany; Fig. 2). None of the abandonment hotspots registered by MODIS for the time period 2000-2012 occurred in Eastern Europe (e.g., Poland, Slovakia) or other European Mountain regions (e.g., the Pyrenees), although all these regions had low to moderate abandonment rates (Fig. 2). Permanent unmanaged farmland was mainly found on the Iberian Peninsula and in
Eastern Europe. Recultivation of unused farmland in 2000-2012 occurred on 24,620 km$^2$, mainly in the Baltic States and on the Iberian Peninsula (Fig. 2).

In terms of forest area changes, most areas in Europe exhibited stable or slightly increasing forest land (Fig. 2, Fig. 3) The total area of forest expansion was 70,300 km$^2$, with hotspots occurring in the Mediterranean (i.e., northern Spain, northern Italy, Western Greece) and the Baltic states (i.e., Estonia, Latvia). Most areas where forestland increased also coincided with areas where farmland or pastures were declining. Hotspots of increase in forestland at the grid-level mainly resembled those at the NUTS-level, but the grid-level analyses highlighted also several smaller hotspots of forestland increase, for example in Scotland, Sardinia, Central Romania, and Hungary (Fig. 3). Deforestation was much less widespread with hotspots in Central Spain, and notable areas of forestland decline in Scandinavia (Fig. 2).

Urban areas increased mainly in Great Britain, particularly in England and here especially in the 1990-2000 period. Other notable hotspots of urban expansion occurred in the Netherlands (particularly in the 2000-2006 period), and around Madrid and Lisbon (Fig. 3). Hotspots of urban expansion were furthermore found in Southern Scandinavia, for example around Helsinki (Finland), Stockholm (Sweden), or the Oresund region in Southern Sweden. Overall, most urban areas remained relatively stable though (Fig. 3), and urban shrinkage was not a notable land change trend in Europe according to our analyses.

Conservation areas increased most strongly in Central and southern Europe, but spatial patterns of conservation area expansion differed markedly among time periods (Fig. 2). Whereas hotspots in increases in protected lands in 1990-2000 occurred mainly in Europe’s South (especially northern and eastern Spain, southern Italy, Greece), most hotspots of protected area expansion in the 2000-2006 occurred in Central and Eastern Europe, predominately in the countries that joined the EU after 2004 (e.g., Estonia, Poland, Slovakia, Hungary, Bulgaria). In total, the conservation area in Europe (IUCN categories I-V) increased by ~577,700 km$^2$ in 1990-2006 (at annual rates of 0.8% and 1%, for 1990-2000 and 2000-2006, respectively)

**Intensity changes within broad land use categories**

Cropland use intensity, measured in terms of fertilizer inputs, showed a heterogeneous pattern in Europe during the time period we assessed. Most NUTS-2 regions within the EU-27 displayed a declining trend in fertilizer application (Fig. 4). This trend was especially prevalent in
Eastern Europe and during the first period we assessed (represented in the grid-level analyses by an increase in the low-intensity class, Fig. 5). In contrast, in Western, Central and Southeastern Europe (e.g., France, Germany, the Netherlands, Bulgaria), the trend in declining fertilizer application rates was particularly prevalent during the second period (2000-2006; Fig. 4). We also found many regions to be characterized by initial increases and decreases in the second period (e.g., Southern Sweden, some regions in Eastern Europe; Fig. 4). Central Italy was a hotspot of increasing fertilizer application in both time periods. Areas of stable fertilizer application rates (i.e., coldspot regions) were mainly found in Europe’s north (where fertilizer application rates were minimal) as well as in southern Germany and northern Italy (where fertilizer application rates were generally relatively high). Overall, an area of ~64,300 km² of cropland was characterized by declining fertilizer application rates, whereas ~178,300 km² showed increasing fertilizer application and ~80,800 km² were characterized as stable (Fig. 5).

Measuring cropland use intensity in terms of outputs showed a clear pattern of increasing crop yields tended in Western Europe and decreased cropland yields in Eastern Europe during 1990-2000 at the NUTS-2 level (Fig. 4). Hotspots of increase were located in Germany, France, Belgium, Luxemburg, the Netherlands and Ireland, whereas hotspots of declining yields were mainly located in southeastern Europe (e.g., Bulgaria, Romania, Hungary; Fig. 5). This pattern changed substantially after 2000, when Eastern Europe showed increasing yield trends, whereas yields in many regions in Europe’s west tended to decrease (Fig. 4). Remarkably, almost all same hotspots of yield decline in 1990-200 became hotspots of yield increase in 2000-206, particular Romania and Bulgaria (Fig. 5). Hotspots of decreases in crop yields in 2000-2006 were mainly clustered in the Mediterranean, particularly in Spain, southern Italy and southern France (Fig. 4), but some hotspots of yield decline also occurred in Western and Central Europe (e.g., Ireland, Germany and Poland) (Fig. 5).

Labor efficiency showed a rather mixed pattern, with regions of increasing and decreasing labor efficiency occurring next to each (Fig. 4). Generally though, labor efficiency tended to increase in Central and Northern Europe during the first time period (1990 – 2000), with hotspots in the Baltic States and the south of Italy. In the second period, labor efficiency generally tended to decrease across Europe, including in many regions identified of hotspots of increasing labor efficiency during the first period (Fig. 4). Interestingly, whereas labor efficiency increased in
many NUTS-2 regions in Eastern Europe during 1990-2000, the second period was characterized by efficiency decreases, especially in Romania and Slovakia (Fig. 4).

In terms of gazing intensity, stocking rates declined in most NUTS-2 regions, especially in Central and Eastern Europe, including most areas in Germany, France, the Benelux countries, and the new accession states in Eastern Europe (Fig. 4), as well as parts of England and Wales as well as northeastern Germany (Fig. 5). Hotspots of increases in livestock heads were mainly found in Ireland and some Mediterranean regions (e.g., Southern Italy, Crete). Overall, Scandinavia and large parts of the Mediterranean were characterized by a relative stability in terms of livestock numbers.

Measuring grazing intensity in terms of the biomass removed from pastures showed a similar polarized pattern than the changes in crop yields. In 1990-2000, most regions in Western Europe were characterized by an increase in biomass harvested from pastures, whereas many Eastern European regions were characterized by decreasing biomass harvests from pastures in this time period (Fig. 4). Hotspots of increase occurred on the Iberian Peninsula (Fig. 4), northern Italy, southern Germany, and the British Isles (Fig. 5). Declining biomass harvests were particularly strong in Western Poland, Bulgaria, and Hungary (Fig. 4), as well as Romania, the Baltic States, and some regions in Finland (Fig. 5). Similar to cropland yields, the situation in 2000-2006 mirrored that in 1990-2000 in Western and Central Europe, with decreasing grazing intensity across much of Western and Central Europe, with the exception of Portugal, Italy and the UK (Fig. 4). In contrast to cropland yields though, grazing intensity continued to decline throughout much of Eastern Europe in 2000-2006, indicating a continuous decline of the importance of livestock grazing.

Regarding forestry, wood harvest volumes decreased in most NUTS-2 regions in Western and Southern Europe during 2000-2006, with hotspots in Northern France, central Italy, and Greece (Fig. 4). In contrast, increasing wood harvesting trends characterized much of central, eastern, and northern Europe, with hotspots in parts of Germany, Poland, the United Kingdom, Scandinavia and the Baltic States (Fig. 4). In 2006-2010, this pattern remained overall very similar, with the exception of Portugal, which became a hotspot of increasing harvest after 2000, and the Baltic states, where harvests decreased after 2006 (Fig. 5). Likely, hotspots of harvesting increase resemble major natural disturbances such as the extensive windthrows in southern
Germany and northern France. Stable areas in terms of wood harvests were found mainly in the Mediterranean, especially Spain (Fig. 4).

Translating harvested volumes to harvesting intensity via relating harvests to increment (see Levers et al., in prep. for details) showed a different pattern than harvesting volume alone. Most NUTS-2 regions in Europe were characterized by an increasing trend in forest harvesting intensity in 2000-2006, with hotspots particularly in southern and western Germany, northern France, southern Sweden, and some regions in the Mediterranean (e.g., Italy, Greece; Fig. 4).

After 2006, harvesting intensity decreased in many regions in southern Europe, central Europe (especially Germany), and Scandinavia. Harvesting intensity decreased in Finland and France in both periods, but increased in Poland and Germany (Fig. 4).

Rotation length decreased in the vast majority of the NUTS-2 regions in Europe, indicating an increase in forestry in those areas. Hotspots of decreasing rotation were found in parts of Great Britain (especially Scotland), as well as the southwestern France, Denmark, and most of the Benelux region (Fig. 4). Hotspots of increasing rotation length (i.e., decreasing forestry intensity) occurred mainly in northern Sweden, some regions in the Czech Republic, England and Italy (especially in the time period 2000-2010). Hotspots of stable rotations length were mainly found in Finland, eastern Austria, Portugal, and some regions in France (Fig. 4).

Human Appropriation of NPP (HANPP), or main system-level metric of land use intensity (Erb et al, under review) displayed a strong north-south divide during the first period, with decreasing HANPP in Europe’s south and increasing HANPP in Central and Northern Europe on NUTS-2 level (Fig. 4). Areas of stable HANPP patterns occurred mainly in Scandinavia, especially in northern Sweden and Finland, as well as the Iberian Peninsula (Fig. 4). Comparing HANPP trends in time showed a relatively inconsistent pattern, with only a few regions consistently decreasing or increasing (Fig. 4). Mentionable exceptions were the southern parts of Germany, showing increasing HANPP trends over the whole period (likely due to the increase of wood harvest in these regions). Comparing HANPP trends across scales showed that in some regions, areas of decreasing and increasing HANPP compensated each other, so that hotspots only appeared at the grid level (Fig. 5). An example of such a region was Estonia for the first time period considered, and southern Sweden for the second time period.
Summarizing across hotspot of area and intensity changes

Summarizing across the individual land use change indicators described above showed interesting patterns and highlighted regions were many land change processes appear to occur in parallel (Fig. 6). Regions with a number of land system change trends with a negative sign (i.e., decreasing area of a particular land use class or decreasing land use intensity in our analyses) during the first period (1990-2000) were especially widespread in Eastern Europe (e.g., Romania, Bulgaria), as well as some Mediterranean areas (e.g., Italy and Portugal). Regions with few or only a single hotspot of land use trends with a negative sign were scattered across Europe and did not show a clear spatial pattern. In the second period (2000-2006), patterns of regions with may co-occurring land change trends were relatively similar to the first time period, with most land change occurring in Eastern Europe, Italy and the Iberian Peninsula (Fig. 6).

Multiple hotspots of land system changes with a positive sign (i.e., increasing area of a particular class or increasing intensity of a particular land use process) in the first period were located mainly in the Baltic countries, in northern Spain, southern Italy, and in the Netherlands (Fig. 6). Few or single hotspots within a NUTS-2 region were mainly found in Eastern Germany, the UK, except for Scotland, as well as in Bulgaria and Romania. In the second period (2000 - 2006), a general increase in the number of positive land system changes per region was observable. Multiple hotspots in this period were located especially in Eastern Europe, the Netherlands, and in the southern parts of Finland and Sweden. Interestingly, reversed patterns can be found in Spain compared to the first period. Overall, hotspots of positive land system change were located primarily in the Mediterranean region, the Baltic countries, the UK, the Netherlands, and in parts of Germany, Sweden, and Finland.

Regions with high transition dynamics, defined here as an accumulation of land change processes regardless of whether they were having a positive or negative sign, in the first period were mainly located in the Mediterranean region, Romania, Bulgaria, and the Baltic countries (Fig. 6). Western and Central Europe showed generally lower levels of land system changes with hotspots in the Netherlands, the UK, Denmark, and some parts of Germany. These patterns remained similar in the second period (2000 - 2006) with generally lower levels of change in the Mediterranean countries but a considerable increase in Eastern Europe and southern Scandinavia. Overall, hotspots of land system changes of the last two decades were detected especially in the
Mediterranean region, Eastern Europe, and the Baltics. Changes were less prominent for Central Europe, except the Netherlands, the UK, and parts of Germany (Fig. 6).

Discussion

We gathered and analyzed a wide range of land change indicators, pertaining to both conversions among broad land use classes and changes in land management intensity, in order to reveal substantial variation in time and space regarding the land use change processes and spatial patterns that affect Europe’s landscapes. The divergent directions and patterns of the different indicators show the added value of addressing these different dimensions of land change: focusing on land cover change indicators only does not reveal the many changes in land systems that have taken place across the period analyzed. The results reported here should be interpreted as a progress report, as major steps in the processing framework of WP 3 are still underway or planned, including the analysis of spatial co-occurrence of different change processes, the assessment of underlying drivers and spatial determinants of change patterns, and the identification of archetypical combinations of drivers and outcomes of land change (see outlook section below). Nevertheless, the analyses presented already highlights a number of interesting insights on broad-scale land change processes in Europe.

Our results showed that the contraction of cropland area has been a major land change process in the EU-27 recently, both in terms of arable land and in terms of permanent cropland (Fig. 2, Fig. 3). Hotspots of cropland abandonment mainly appear to occur on land marginally suited for agriculture (e.g., mountain regions such as the Alps or the Pyrenees, the Mediterranean, northern Europe), thereby confirming earlier studies highlighting some of these regions (MacDonald et al., 2000, Rutherford et al., 2008, Navarro and Pereira, 2012, Müller et al., 2013, Stellmes et al., 2013). Although cropland declined in most regions across Europe, cropland shrinkage was small in those regions in Western and Central Europe well-suited for farming, a region mainly characterized by relatively stable cropland patterns and where also the few hotspots of farmland expansion occurred. Interestingly, although we expected farmland expansion in Eastern Europe, it was not very widespread in the 2000-2006 period (and also in the 2000-2012 MODIS analyses), potentially because the effects of the EU accession of Eastern Europe’s countries were not yet manifested in our data. Our a-priori hypothesis had been that expansion had occurred as Eastern Europe agricultural sectors rebounded from the developments
after the breakdown of socialism, which led to a drastic reorganization of agricultural sectors and much land abandonment (Müller et al., 2009, Baumann et al., 2011, Alix-Garcia et al., 2012).

In contrast to the general trend in cropland decline or stability across Europe, we found spatially and temporally very diverse patterns of cropland intensity change. The most striking pattern we identified was strong divide between Europe’s West and East, with increasing cropland use intensity in Western Europe (i.e., higher fertilizer use, yield increases) and declining intensity in Eastern Europe and some parts of the Mediterranean (Fig. 4). Again, a plausible explanation for these patterns appear to be the legacy of socialism, during which agricultural sectors are generally thought to have underperformed compared to Western Europe, and the breakdown of socialism resulting in a shrinkage of agricultural sectors and a decline in capital-intensive farming (e.g., heavy use of pesticides and fertilizer) after 1989 in Eastern Europe. In agreement with this hypothesis is that our results show a strong East/West divide during 1990-2000, but a more diverse spatial pattern in 2000-2006, when many agricultural sectors of Eastern countries recovered.

A major finding from our study in the context of cropland intensity was that different indicators result in very different spatial patterns of cropland use intensity and highlight different hotspots of increasing and decreasing intensity, as well as different coldspots of stability (Fig. 4, Fig. 5). Most importantly, increasing input intensity (i.e., fertilizer use in our case) is not necessarily related to increasing output intensity (i.e., yields) and vice versa, highlighting the multidimensional nature of land use intensity and the need for a range of indicators pertaining to inputs, outputs, and system-level changes to capture the full range of effects of intensification (Erb et al., 2013, Kuemmerle et al., 2013).

Forest area generally tended to increase across most of Europe, often in those regions characterized by cropland and pasture decline (Fig. 2, Fig. 3) and thus further emphasizing the general trend of decreasing land use intensity in many of Europe’s marginal areas. Most hotspots of forest increase occurred in the Mediterranean basin, where urbanization and an abandonment of traditional rangeland management are widespread (Poyatos et al., 2003, Piquer-Rodríguez et al., 2012, Stellmes et al., 2013), and in Eastern Europe, where the collapse of socialism has led to similar socio-economic trends (Müller et al., 2013). These forest trends can thus be interpreted as being part of long-term land change processes in the context of the forest transition, which generally happened earlier in Western and Central European countries compared to Eastern and southern Europe (Rudel, 1998, Rudel et al., 2005, Kuemmerle et al., 2011, Meyfroidt and
Lambin, 2011). Interestingly, our work also highlights that country-level analyses of forest dynamics may mask important patterns at finer spatial scales (Fig. 2, Fig. 3), for example forest loss due to urbanization and thus the spatial segregation of loss and increase within a country which we found in our results for example for the UK, the Netherlands and Belgium and some Scandinavian countries, similar to what has been shown or the United States (Ramankutty et al., 2010).

Our results also showed that changes in forest land were spatially not highly correlated to changes in harvesting. More importantly, harvesting patterns in terms of timber volumes extracted were highly driven by forest productivity (Fig. 4), with higher harvesting in the more productive forests of central Europe and Scandinavia compared to the Mediterranean. This picture changed markedly once timber volume was normalized against the increment, with a general trend of increasing intensity in Central and Eastern Europe, highlighting the need to account for system characteristics when assessing intensity changes in forestry (Luyssaert et al., 2011, Kuemmerle et al., 2013).

Conservation has become a major land use type in Europe during the last two decades, with substantial increases in conservation area in most regions in Europe (Fig. 2). Clearly, these increases relate to major policy changes in Europe regarding nature protection, most importantly the 1997 birds directive and the 1992 habitat directive (Jones-Walters and Čivić, 2013). Accession to the EU requires a country to set aside a substantial part of its territory for nature protection, a trend clearly resembled in our results in the hotspots of conservation area expansion in Europe’s south in the 1990-2000 period, and in Eastern Europe after 2000. We caution though the expansion of conservation land does often not lead to the exclusion of other land uses, because many Natura2000 sites permit low-intensity land use within their boundaries and there is a general trend to integrated land use and conservation goals within the same landscapes (e.g., in the form of biosphere reserves).

On a more general level, our analyses of hotspots and coldspots revealed the complex spatiotemporal nature of change processes occurring in Europe. With few exceptions (e.g., farmland abandonment/forest expansion, see above), we did not identify clear patterns of co-occurrence of different land use processes. Most importantly, area changes were not necessarily related to changes in management intensity. For example, farmland contraction co-occurred with intensification in some regions in Western Europe (i.e., a polarization of land use), but not in other, often neighboring regions. Further research is needed to unravel the drivers of these spatial
patterns, and the bundles of co-occurring or exclusive land change processes across Europe.

Nevertheless, our analyses emphasize the need for accounting for both, area changes and intensity changes, when assessing land change in Europe, and to assess land change in a spatially explicit manner across large regions to reveal change patterns.

While we gathered a comprehensive and largely homogenized set of land change indicators, each of them based on substantial efforts in terms of data collection and homogenization, and each indicator checked for robustness (see deliverable D3.1 for details) a number of factors contributing uncertainty need mentioning. First, we did not cover a few important land change processes due to a lack of spatially explicit datasets, for example in terms of cropland use intensity (e.g., mechanization, pesticide use) or forestry intensity (e.g., afforestation, tree species changes due to management, mechanization, fertilizer use). Second, several of the input layers we used for capturing intensity are based on statistical data, which are sometimes of unknown reliability (e.g., fertilizer use data from post-socialist Eastern Europe). Third, because land use intensity statistics are often only available at coarse scale (e.g., NUTS-2), translating these data to the grid-level requires disaggregation tools, which sometimes need to make strong assumptions (Neumann et al., 2009, Temme and Verburg, 2011). Disaggregation also require substantial input data such as land cover maps (Kuemmerle et al., 2013), meaning that disaggregated intensity changes are not fully independent from area change maps. Finally, several of our input data represent snapshots in time, which may not be problematic for those indicators capturing conversions, but could affect our intensity measures because temporally and spatially variable phenomena may affect management intensity strongly (e.g., drought effects on yields, storm legacies for forest harvesting).

Outlook

Our analyses clearly highlight the diverse and complex spatiotemporal patterns of land change in Europe, and the importance of considering both, conversion among broad land use classes, and management intensity changes within these classes to understand land system change. Identifying hotspots where land use changes rapidly, as well as coldspots where land use remains stable is crucial for better understanding the outcomes of land change for ecosystem service flows, for assessing the trade-offs and synergies among different land uses, and to target policies in the context of fostering multifunctionality, or emphasizing particular production or conservation goals.
The results presented here should be seen as a first step towards understanding the spatial patterns and co-occurrence of different land change processes at fine spatial scales and at the pan-European scale. Building upon the result of this work, we will continue to assess key land system changes pertaining to agriculture, forestry, urbanization and nature conservation in Europe, regarding the relative importance of changes among broad land use classes relative to changes in the intensity within these classes, and in terms of the co-occurrence of different land change processes in work package 3 in VOLANTE will continue. Specifically, we will carry out further, more complex analyses to unravel bundles of co-occurring land change processes and to understand spatial autocorrelation in the land change processes assessed, and we will extend the temporal depth of some of our analyses. This will also be accompanied by further robustness checks of our results. We will also carry out comprehensive analyses of the spatial determinants and underlying drivers of land change processes to understand what produces the spatial we are observing using spatial statistical models (deliverable 3.3). Finally, we will use spatial clustering techniques and semi-qualitative methods to identify archetypical combinations of drivers and outcomes of land change processes (deliverable 3.4), which will form the basis for interpreting past and future land change within the VOLANTE pathway analyses (WP11).

Acknowledgements

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spatially explicit indicator for biodiversity on agricultural land in the EU. *Ecological Indicators, in press.*


Table 1: Land use changes processes and indicators considered in the analyses in this paper to characterize land system change in Europe for the time period 1990 – 2000 – 2006 (– 2010).

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<th>Area change</th>
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<td>Cropland area change</td>
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<td>Change in cropland area</td>
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<td>Protected area changes</td>
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**Figures captions**

Fig. 1: Area changes and management intensity changes in Europe’s (a) cropland (source: FAOSTAT) and (b) forests (Sources: Kuusela (Kuusela, 1994a), Forest Europe (2011), Gold (Gold, 2003), Gold et al. (2006) Vilen et al. (2012))

Fig. 2: Hotspots of area changes among broad land use categories at the NUTS-2 level based on a range of data sources (see Methods and Materials). Dark grey determines NUTS-2 regions with decline trends whereas light grey refers to areas with increasing area trends.

Fig. 3: Hotspots of area changes among broad land use categories at the 1-km grid level based on a range of data sources (see Methods and Materials).

Fig. 4: Hotspots of intensity changes within broad land use categories at the NUTS-2 level based on a range of data sources (see Methods and Materials). Dark grey determines NUTS-2 regions with decline trends whereas light grey refers to areas with increasing area trends.

Fig. 5: Hotspots of intensity changes within broad land use categories at the 1-km grid level based on a range of data sources (see Methods and Materials).

Fig. 6: Summary maps depicting the number of times each NUTS-2 region was highlighted as a hotspot of land use change in the analyses of individual indicators. Negative hotspots refer to regions of declining area (e.g., cropland decline) or decreasing intensity (e.g., decreasing fertilizer use). Positive hotspots refer to regions of increasing area (e.g. forest expansion) or increasing intensity (e.g., higher forest harvesting intensity).
APPENDIX 1: MAPS OF HOTSPOTS OF DIFFERENT LAND USE CHANGE PROCESSES IN THE EU-27

Part 1: Conversions among broad land use classes at the level of NUTS2 regions
Cropland area change %
1990/2006

Cropland expansion

- 100% top 10% increase
- 20-90%
- 10%
- -10%
- -20-90%
- -100% top 10% decrease

Cropland decline

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Changes in permanent crop area %

2000/2006

Expansion of permanent crop area

- 100% top 10% increase
- 20-90% N = 73
- 10% bottom 20% increase
decrease
- -10% N = 155
- -20-90%
- -100% top 10% decrease

Decline of permanent crop area

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Changes in permanent crop area %

1990/2006

Expansion of permanent crop area
- 100% top 10% increase
- 20-90% N = 55
- 10% bottom 20% increase
decrease
- -10% N = 167
- -20-90% top 10% decrease

Decline of permanent crop area

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Change of Agricultural abandonment %

2000/2012

abandoned area increase
-100% top 10% increase
20-90% N = 217
10% bottom 20% increase decrease
-10% N = 0
-20--90%
-100% top 10% decrease

abandoned area decrease

---

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Change of Agricultural recultivation %

2000/2012

recultivated area increase

-100% top 10% increase
20-90% N = 198
10% bottom 20% increase decrease
-10% N = 0
-20-90% recultivated area decrease
-100% top 10% decrease

0 250 500 Kilometers

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Protected area changes %
1990/2006

Protected area expansion

- 100% top 10% increase
- 20-90% N = 223
- 10% bottom 20% increase decrease
- -10% N = 0
- -20-90% N = 0
- -100% top 10% decrease

Protected area decline

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Part 2: Changes in management intensity within broad land use classes at the level of NUTS2 regions
Changes in Fertilizer input intensity %

2000/2006

class 1: < 50kg / ha

Fertilizer increase

- 100% top 10% increase
- 20-90% N = 102
- 10% bottom 20% increase
- -10% decrease
- -20- -90% N = 129
- -100% top 10% decrease

Fertilizer decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number 01
Cartographic References: ETRS 1989 LAEA
Changes in Fertilizer input intensity %
1990/2006

class 1: < 50kg / ha

Fertilizer increase

-100% top 10% increase
20-90% N = 138
10% bottom 20% increase
decrease
-10% N = 93
-20--90% Fertilizer decrease

-100% top 10% decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Changes in Fertilizer input intensity %

1990/2000

class 2&3: > 50kg / ha

Fertilizer increase
- 100% top 10% increase
- 20-90% N = 84
- 10% bottom 20% increase
- -10% decrease
- -20--90% N = 147
- -100% top 10% decrease

Fertilizer decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Changes in Fertilizer input intensity %

2000/2006

class 2&3: > 50kg / ha

Fertilizer increase

-100% top 10% increase
20-90% N = 129
10% bottom 20 % increase
decrease
-20-90% N = 102
-100% top 10% decrease

Fertilizer decrease

---

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

---

Kilometers
Changes in Fertilizer input intensity %

1990/2006

class 2 & 3: > 50kg / ha

Fertilizer increase

- 100% top 10% increase
- 20-90% N = 129
- 10% bottom 20% increase
- -10% decrease
- -20--90% N = 102
- -100% top 10% decrease

Fertilizer decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Yield changes for major crops %
1990/2000

Yield increase
-100% top 10% increase
20-90% N = 115
-10% bottom 20% increase decrease
-20--90% N = 104
-100% top 10% decrease

Yield decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Yield changes for major crops \% 1990/2006

Yield increase
- 100\% top 10\% increase
- 20-90\% N = 97
- 10\% bottom 20\% increase decrease
- -10\% N = 122
- -20-90\%
- -100\% top 10\% decrease

Yield decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Labour efficiency
by employee %
2000/2006

efficiency improvement

- 100% top 10% increase
- 20-90% N = 86
- 10% bottom 20% increase decrease
- -10% N = 70
- -20--90%
- -100% top 10% decrease

efficiency reduction

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Change of biomass removal on grazing land %

2000/2006

grazing increase

-100% top 10% increase
20-90% N = 104
10% bottom 20% increase
decrease
-10% N = 105
-20-90% N = 105
-100% top 10% decrease
grazing decrease

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Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
HANPP Change %
1990/2000

HANPP increase
- 100% top 10% increase
- 20-90% N = 63
- 10% bottom 20% increase
- -10% decrease
- -20--90% N = 84
- -100% top 10% decrease

HANPP decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Wood harvesting intensity Change %
2006/2010

Harvesting intensity increase

- 100% top 10% increase
- 20-90% N = 169
- 10% bottom 20% increase decrease
- -10% N = 228
- -20--90% top 10% decrease

Harvesting intensity decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Changes in Forest rotation length
2000/2010

forest rotation length increase

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Description</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100%</td>
<td>top 10% increase</td>
<td>N = 34</td>
</tr>
<tr>
<td>20-90%</td>
<td></td>
<td>N</td>
</tr>
<tr>
<td>-10%</td>
<td>bottom 20% increase</td>
<td></td>
</tr>
<tr>
<td>-20-90%</td>
<td>decrease</td>
<td>N = 70</td>
</tr>
<tr>
<td>-100%</td>
<td>top 10% decrease</td>
<td></td>
</tr>
</tbody>
</table>

forest rotation length decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Changes in Forest rotation length 1990/2010

forest rotation length increase
-100% top 10% increase
20-90% N = 34
10% bottom 20% increase
decrease
-10% N = 70
-20-90% top 10% decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number 01
Cartographic References: ETRS 1989 LAEA
Part 3: Conversions among broad land use classes at the 1-km grid level
Cropland area change

1990/2006

Cropland expansion

-100% top 5% increase
-5-95%
-5% bottom 10% increase
decrease
-5-95%
-100% top 5% decrease

Cropland decline

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Changes in permanent crop area
2000/2006

Expansion of permanent crop area
-100% top 5% increase
5-95%
5% bottom 10% increase
decrease
-5-95%
-100% top 5% decrease

Decline of permanent crop area

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Changes in permanent crop area
1990/2006

Expansion of permanent crop area
-100% top 5% increase
-5 - 95% increase
decrease
5% bottom 10% increase
decrease
-5 - -95% top 5% decrease
Decline of permanent crop area

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Pasture area change

2000/2006

Pasture expansion
- 100% top 5% increase
- 5-95%
- bottom 10% increase
decrease
- 5 - 95%
- 100% top 5% decrease

Pasture retreat

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Pasture area change
1990/2006

Pasture expansion
- 100% top 5% increase
- 5-95%
- 5%
- bottom 10% increase
decrease
- 5 -95%
- top 5% decrease

Pasture retreat

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Urban extent change

1990/2000

Urban area expansion
- 100% top 5% increase
- 5-95%
- 5% bottom 10% increase
decrease
- -5%
- -5 - -95%
- -100% top 5% decrease

Urban area decline

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Urban extent change
1990/2006

Urban area expansion
- top 5% increase
- 5-95%
- 5%
- bottom 10% decrease
- 5 - 95%
- 100%

Urban area decline

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Part 4: Changes in management intensity within broad land use classes at the 1-km grid level
Changes in Fertilizer input intensity 1990/2006

Fertilizer input < 50kg / ha

- decrease
- no change
- increase

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Changes in Fertilizer input intensity

2000/2006

Fertilizer input
> 50kg / ha

decrease
no change
increase

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH,EFI,IVM,UBER,UNIKLU
Date: 06/2013
Version Number 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Yield changes for major crops 2000/2006

Yield increase
- 100% top 5% increase
- 5-95%
- 5%
- bottom 10% increase
decrease
- -5%
- -5% -95%
- -100% top 5% decrease

Yield decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Yield changes of major crops 1990/2006

Yield increase

100% top 5% increase
5-95%
5% bottom 10% increase
-5% decrease
-5 - -95%
-100% top 5% decrease

Yield decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Grazing animal changes 1990/2000

- Blue: decrease
- Gray: no change
- Red: increase

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Grazing animal changes 2000/2006
Grazing animal changes 1990/2006

- decrease
- no change
- increase

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA
Change of biomass removal on grazing land 1990/2000

grazing increase
-100% top 5% increase
5-95%
5% bottom 10% increase
decrease
-5 - -95%
-100% top 5% decrease

grazing decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Change of biomass removal on grazing land
2000/2006

grazing increase
-100% top 5% increase
5-95%
5% bottom 10% increase
decrease
-5 -95%
-100% top 5% decrease

grazing decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers

grazing increase
- 100% top 5% increase
- 5-95%
- 5%
- bottom 10% increase decrease
- -5%
- -5 - -95%
- -100% top 5% decrease

grazing decrease

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Wood harvest change

1990/2000

forest expansion
- 100% top 5% increase
- 5-95%
- bottom 10% increase
- -5%
- -5-95%
- -100% top 5% decrease

forest retreat

Project: Volante-FP7-ENV-2010-265104
Institutions: CPH, EFI, IVM, UBER, UNIKLU
Date: 06/2013
Version Number: 01
Cartographic References: ETRS 1989 LAEA

0 250 500 Kilometers
Figure 2

- **Cropland area change**
- **Permanent crop area change**
- **Abandoned and fallow farmland**
- **Abandoned farmland 2000 - 2012**
- **Permanent unmanaged 2000 - 2012**
- **Recultivation 2000 - 2012**
- **Pasture area change**
- **Forest area change**
Figure 2, continued

Urban extent change

1990 - 2000
2000 - 2006
1990 - 2006

Protected area change

1990 - 2000
2000 - 2006
1990 - 2006

- Red: Hotspots of area increase (top 10% of increases)
- Purple: Coldspots of area change (bottom 10% of increases and decreases)
- Blue: Hotspots of area decrease (top 10% of decreases)
Figure 3, continued

Urban extent change

Protected area change

- Red: Hotspots of area increase (top 5% of increases)
- Purple: Coldspots of area change (bottom 5% of increases and decreases)
- Blue: Hotspots of area decrease (top 5% of decreases)
Figure 4

Changes in fertilizer input intensity

Yield changes for major crops

Labor efficiency change (by worker)

Grazing animal changes (heads)

Changes in biomass removal via grazing
Figure 4, continued

HANPP change

1990 - 2000

2000 - 2006

2000 - 2006

Wood harvest volume changes

2000 - 2006

2006 - 2010

2000 - 2010

Wood harvest intensity change

2000 - 2006

2006 - 2010

2000 - 2010

Changes in forestry rotation length

1990 - 2000

2000 - 2010

1990 - 2010

Colours:
- Red: Hotspots of intensity increase (top 10% of increases)
- Purple: Coldspots of intensity change (bottom 10% of increases and decreases)
- Blue: Hotspots of intensity decrease (top 10% of decreases)
Figure 5

Changes in fertilizer input intensity (> 50 kg/ha class)

Yield changes for Major Crops

HANPP change

Changes in grazing animals

1990 - 2000

2000 - 2006

1990 - 2006
Changes in biomass removal

Wood harvest change

Hotspots of area increase (top 5% of increases)
Coldspots of area change (bottom 5% of increases and decreases)
Hotspots of area decrease (top 5% of decreases)
Figure 6

Sum of negative hotspots

Sum of positive hotspots

Sum of positive and negative hotspots