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Drivers of forest harvesting intensity patterns in Europe

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ABSTRACT

Forests provide humankind with essential raw materials and the demand for these materials is increasing. Further expanding forestry into unmanaged forests is environmentally costly and increasing forest area via plantations will not immediately lead to increased wood supply. Thus, just like in agriculture, forestry faces the challenge how to intensify forest management in existing production forests in sustainable ways. Yet, our current understanding of what determines forest management intensity is weak, particularly at broad scales, and this makes it difficult to assess the environmental and social trade-offs of intensification. Here, we analyse spatial patterns of forest harvesting intensity as one indicator for forest management intensity across Europe, a region where most forests suitable for production are already in use and where future intensification is likely. To measure forest harvesting intensity, we related harvested timber volumes to net annual increment for the period 2000–2010. We used boosted regression trees to analyse the spatial determinants of forest harvesting intensity using a comprehensive set of biophysical and socioeconomic explanatory variables. Our results show that forest harvesting intensity varied markedly across Europe and harvested timber volumes were well below the increment in most regions. Harvesting intensity was especially high in southern Finland, southern Sweden, southwestern France, Switzerland, and the Czech Republic. The spatial patterns of forest harvesting intensity were well explained by forest-resource related variables (i.e., the share of plantation species, growing stock, forest cover), site conditions (i.e., topography, accessibility), and country-specific characteristics, whereas socioeconomic variables were less important. We also found the relationship between forest harvesting intensity and some of its predictors (e.g., share of plantation species, accessibility) to be strongly non-linear and characterised by thresholds. In summary, our study highlights candidate areas where potentials for sustainably intensifying timber production may exist. Our analyses of the spatial determinants of harvesting intensity also provides concrete starting points for developing measures targeted at increasing regional wood supply from forests or lowering harvest pressure in regions where forests are heavily used. Finally, our study emphasises the importance for systems' understanding for designing and implementing effective sustainable forest management policies.

1. Introduction

Land use provides humanity with essential food, fibre, and bioenergy, but is also a major force of global environmental change (MA, 2005; Haberl et al., 2007; Pereira et al., 2010). As fertile land is getting scarce (Lambin and Meyfroidt, 2011) and further expansion of land use into remaining wildlands incurs high environmental costs, future production increases will, to a large extent, have to rely on sustainably intensifying land already in use (Foley et al., 2011; Tilman et al., 2011). Yet, assessing where future production can be increased and understanding the trade-offs of intensification is currently limited by incomplete knowledge about the spatial patterns and drivers of intensification pathways, especially at broad geographic scales (Verburg et al., 2009; Erb, 2012; Lambin et al., 2001).

This is particularly the case in forestry, where the spatial patterns of forest management intensity and the drivers that produce these patterns remain highly unclear. This is unfortunate, because

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forest management effects on forest ecosystem functioning vary substantially depending on management intensity. For example, the intensity by which forests are managed affects forest structure (Vilén et al., 2012), soils (Jandl et al., 2007), biogeochemical cycles (Nabuurs et al., 2013; Luyssaert et al., 2012), biodiversity (Paillet et al., 2010), and ecosystem service provisioning (Gamfeldt et al., 2013). Understanding the spatial patterns of forest management intensity and its drivers is therefore important for assessing the environmental trade-offs of forestry and for identifying opportunities for sustainable intensification.

Assessing forest management intensity is challenging because intensity itself is a complex term, encompassing multiple dimensions (Schall and Ammer, 2013). Consequently, forest management intensity has been examined using a wide range of indicators, including harvested timber volumes, forest structural parameters (e.g., the difference between potential and actual biomass storage), stand establishment practices, tree species composition, length of rotation periods, human appropriated net primary production, or the amount of fertiliser, herbicides, and machinery used (Luyssaert et al., 2011; Forest Europe and UNECE FAO, 2011; Duncker et al., 2012). Intensity metrics, which relate inputs (e.g., capital), outputs (e.g., harvested timber volumes), or system properties (e.g., ecosystem productivity) to each other, can provide insights into land use intensity patterns and drivers (Erb et al., 2013; Kuemmerle et al., 2013). For example, interpreting harvested timber volumes without considering ecosystem productivity could be misleading as the same volume of timber extracted from forest systems with high or low productivity may indicate very different levels of forest harvesting intensity. By expressing harvested timber volumes in relation to the net annual increment, forest harvesting intensity can be assessed across large regions.

Unfortunately, studies assessing forest harvesting intensity have either focussed on the national scale (e.g., relying on national forest resource assessments, (Kuusela, 1994; Forest Europe and UNECE FAO, 2011), or on small study regions (see Schall and Ammer, 2013 for an overview), both of which precludes understanding spatial patterns of management intensity. Only two studies addressed drivers of forest harvesting patterns at broad spatial scales. Analysing timber harvesting patterns in European Russia showed that road density, forest composition, and total forest area were important determinants of harvesting patterns (Wendland et al., 2011). A range of spatial variables including tree species composition, slope, forest coverage, proximity to cities, and conservation areas allowed mapping different forest management systems in Europe using an expert-based approach (Hengeveld et al., 2012). We know of no study explicitly addressing broad-scale patterns of forest harvesting intensity.

Evidence on the drivers of forest owner's decisions to manage their forest intensely or not was only derived from local-scale case studies. These studies, mainly focussing on non-industrial, private forest owners, show that a range of policy, forest resource, and market factors are potentially important in determining timber volumes extracted (Beach et al., 2005; Amacher et al., 2003). For example, forest management plans, property size, and income from agriculture determined harvesting decisions in Norway (Størdal et al., 2008), ownership size and type shaped harvesting decisions in the southern US (Arano and Munn, 2006), or the demand for wood products and associated price changes were important drivers of harvesting decisions in the US and Australia (Adams et al., 1991; van Putten and Jennings, 2010). Furthermore, population density, forest size, and distance to urban areas influenced harvesting in the US (Wear et al., 1999; Munn et al., 2002). Yet, none of these studies addressed patterns and drivers of forest harvesting intensity for larger regions. Clearly, there is a research gap at the regional scale, which is unfortunate because of its major importance for policy making and for mitigating the impacts of global environmental change (Wu, 2013).

Regression models are powerful tools to assess drivers and determinants of land use patterns (Müller et al., 2011; Baumann et al., 2011; Wendland et al., 2011). Algorithmic models are particularly promising because they do not impose any a priori relationship between target and predictor variables. Fewer requirements on the data structure make them well-suited to investigate the complex and often non-linear interactions between predictors and response in land systems. Algorithmic models, such as boosted regression trees (BRT), generally attain a higher model fit and predictive accuracy than traditional statistical approaches (Elith et al., 2006; Lakes et al., 2009; Lin et al., 2011). Because of their higher predictive accuracy, better ability to generalise from data, and possibility to handle large heterogeneous data sets, algorithmic models are gaining growing attention in ecology (Leathwick et al., 2006; De'ath and Fabricius, 2000) and land change science (Müller et al., 2013; Gellrich et al., 2008), but no study has so far used BRTs to assess spatial determinants of forest harvesting intensity.

In this study, we sought to quantify and understand broad-scale spatial determinants of forest harvesting intensity patterns across the European Union (EU-27) plus Norway and Switzerland. As intensity metric, we used the ratio of harvested timber volume (fellings and harvest losses) and net annual increment volume (hereafter referred to as "forest harvesting intensity") because this ratio is an important criterion to assess the sustainability of forest resource use. As explanatory variables, we focused on selected factors that are indirect proxies of the underlying drivers of forest harvesting intensity (hereafter referred to as "spatial determinants").

Europe is an interesting case for assessing forestry intensity since forest use in Europe has a long history. After centuries of extensive deforestation, Europe's forests increased in the 19th and 20th century as a result of farmland abandonment, afforestation, and nature protection (Kaplan et al., 2012; Rudel et al., 2005), and forests now cover 37% of Europe's terrestrial surface. Though forest cover has increased steadily during the last decades (0.37% per year, Forest Europe and UNECE FAO, 2011), forest harvesting intensity also remarkably increased from 58% (1990) to 62.4% (2010) and is expected to increase further (UNECE and FAO, 2011; Böttcher et al., 2012). Forest cover is distributed very unevenly across Europe and the region is furthermore characterised by large environmental (e.g., boreal to Mediterranean), historical (e.g., capitalism vs. socialism), ethnic, and economic (highly industrialised vs. less industrialised economies) heterogeneity. How this heterogeneity relates to spatial patterns in forest harvesting intensity remains largely unclear. Understanding forest harvesting intensity is one key aspect for assessing forest management intensity. To ensure the sustainable intensification of forest management in light of growing demands for timber products would, however, require a range of indicators addressing the multidimensionality of forest management intensity.

We compiled time series of sub-national forest harvesting intensity patterns in Europe between 2000 and 2010 and used boosted regression trees to quantify the influence of a set of biophysical, infrastructure, and socioeconomic variables in shaping these patterns. Specifically, we ask the following research questions:

1. What are the spatial patterns of forest harvesting intensity in Europe?
2. What are the most influential spatial determinants of these patterns and what is their relative importance?
3. What is the nature of the relationships between forest harvesting intensity and its spatial determinants?