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Drivers of changes in agricultural intensity in Europe

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ABSTRACT

The global demand for agricultural products will increase in the 21st century, unless major transformations in consumptive behaviour occur. To a large extent, production increases in agriculture will depend on intensifying existing agricultural systems. Yet, our understanding of what determines the spatial patterns of agricultural intensity and changes therein is limited. Here, we analysed agricultural intensity changes in Europe focussing on yields and fertiliser application for six major crop-type groups for the period 1990–2007. We applied random effects panel regressions to analyse the spatial determinants of intensity changes using a suite of biophysical and socio-economic variables. We found that yields increased and mineral nitrogen application decreased by approximately 10%, suggesting a decoupling of changes in output and input intensity in Europe's agricultural systems. Yields and nitrogen application across crop-type groups were particularly high in Western and Central Europe, whereas Eastern Europe was characterised by lower yields and nitrogen application. We also found strong sub-national variation in intensity levels in respect to crop-type groups and indicators. Higher yields were typically related to higher fertilisation, high soil quality, less growing degree days, and high labour productivity. Higher nitrogen application rates, in turn, were related to high soil water and carbon contents, and high labour productivity. Our study provides insights into broad-scale agricultural intensity patterns in Europe that allow for identifying trade-offs between agriculture and the environment, as well as entry points for regionalised, targeted policy making towards a more sustainable management of Europe land systems.

1. Introduction

Land use has affected more than 75% of the Earth's ice-free surface (Ellis and Ramankutty, 2008), making land use a major driver of global environmental change (Verburg et al., 2015). Among land uses, agricultural areas are responsible for the largest environmental impacts of humans on natural systems (Kastner et al., 2012; Balmford et al., 2012), such as the widespread loss and degradation of ecosystems and biodiversity (Newbold et al., 2015), increased greenhouse gas emissions (Burney et al., 2010), or alterations of global nitrogen (Galloway et al., 2008) and phosphorus (Cordell et al., 2009) cycles.

Future growth in population and consumption (Godfray 2014; Reisch et al., 2013) and the rising role of bioenergy crops (Beringer et al., 2011) will increase the global demand for agricultural products over the next decades (Schneider et al., 2011; Wirsenius et al., 2010). As fertile land is becoming scarce (Lambin and Meyfroidt, 2011) and expanding agriculture further will entail substantial trade-offs (Garnett et al., 2013; Eitelberg et al., 2015), future production increases will have to come to a large extent from intensifying agricultural land already in use (Tilman et al., 2011). Yet, agricultural intensification is an understudied land-use change process (van Vliet et al., 2015b) and our knowledge on the patterns and drivers and determinants of agricultural intensification remains incomplete, especially at broad geographic scales (Erb, 2012).

One reason for this knowledge gap is that agricultural intensity in itself is a complex phenomenon that can be measured in terms

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of input metrics (e.g., land, labour, use of fertilisers, pesticides, and machinery), output metrics (e.g., yields, caloric/protein/monetary value), or system metrics (e.g., yield gaps, human appropriated net primary production) (Erb et al., 2013). While progress has recently been made in mapping spatial patterns of agricultural intensity (see Fritz et al. (2015) for global cropland and field size, Estel et al. (2016) for cropland-use intensity in Europe, Robinson et al. (2014) for the global distribution of livestock, Temme and Verburg (2011) for fertiliser input and livestock density in Europe, Neumann et al. (2010) for global yield gaps, Siebert et al. (2010) for global patterns of cropland use intensity, or Monfreda et al. (2008) for global patterns of croplands and crop yields) and identifying drivers of agricultural land-use change based on case-study evidence (van Vliet et al., 2015a), our knowledge of what drives changes in these patterns remains very limited (Kuemmerle et al., 2013), especially at large geographic scales that are important for political decision-making (Wu, 2013).

Only a few studies have quantitatively assessed the drivers and determinants of changes in agricultural intensity at large geographic scales. Population and economic growth induced higher global fertiliser application rates (input metric) between 1960 and 2000 (Tilman et al., 2001), higher global caloric crop yields (output metric) were strongly associated with higher nitrogen inputs and to a lesser degree to higher precipitation, potential evapotranspiration, and elevation between 1965 and 2005. Higher soil pH values had a negative effect on crop yields whereas per capita GDP, as a measure of economic status, was positively related to crop yields in wealthier countries and negatively in poorer countries (Tilman et al., 2011). Global grain yields in the year 2000 were higher in areas closer to optimal temperature and higher precipitation, while higher efficiencies in grain production were related to higher fertiliser application, the presence of irrigation, market influence, and better accessibility (Neumann et al., 2010). Global agricultural intensification between 1990 and 2005, measured as the ratio between yields and cultivated area, was positively related to conservation programs, crop cover, and cereal imports, and negatively related to agricultural production and agricultural workforce (Rudel et al., 2009). However, although existing work highlights the value of large-scale analyses for understanding patterns and changes of agricultural intensity, these studies mainly focus on national-level data and leave unclear what drives agricultural intensity changes on fine-scale, subnational levels.

This is unfortunate as these scales are particularly important for policy making that seeks to address the drivers and impacts of global environmental change (Wu, 2013). In light of the need to shift to more sustainable land use (UNDESA, 2012; Pedroli et al., 2015), decision makers need fine-scale, reproducible, comparable, and quantitative information on spatial patterns, changes, as well as drivers and determinants of agricultural intensity. This information should be available for a large enough geographic coverage and match units of political decision-making to allow for designing and implementing effective and spatially targeted measures to foster future sustainable land use.

Europe provides an interesting example to study drivers and determinants of changes in agricultural intensity due to several reasons. First, it offers a large geographic extent and data with subnational resolution for fine-scale analyses matching units of political decision-making. Second, agricultural areas are widespread across the European Union, accounting for approximately half of the land surface (EC 2013; Stoate et al., 2009). Third, most agricultural land-use change in Europe occurred along intensification gradients over the last decades, while the net agricultural area remained nearly stable (Rounsevell et al., 2012). Fourth, agricultural intensity varies substantially across Europe due to the pronounced differences in environmental conditions (e.g., boreal to Mediterranean), history (e.g., capitalism vs. socialism), ethnic composition, and economic status (highly industrialised vs. less industrialised economies) (Jepsen et al., 2015). How this heterogeneity relates to changes in the spatial patterns of agricultural intensity in Europe, however, remains unclear.

Studies that focus on sub-national patterns and drivers and determinants of agricultural intensity in Europe are rare and were often restricted in space (e.g., only for the EU15) or time (e.g., only one target year). Existing work also typically focussed on a single intensity indicator, a limited number of crop types, and either arable areas or grasslands. For example, lower arable land-use intensity and higher grassland-use intensity in terms of nitrogen application in five European countries for the year 2000 were related to poor accessibility and soil conditions, as well as water shortage (Temme and Verburg, 2011). Yields of selected crops increased across the EU15 between 1990 and 2003 with increasing economic size of farms (i.e., standard gross margins), increasing input application (e.g., fertiliser, irrigation), increasing share of arable land per utilised agricultural area, and increasing crop specialisation (Reidsma et al., 2009). Similarly, high elevation and less-favoured areas were negatively associated with crop yields, while temperature and precipitation were often related to yields in concave ways (Reidsma et al., 2010, 2007). Finally, higher livestock occurrence were related to higher precipitation, lower relief energy, better soils, and favourable landscape configuration (Neumann et al., 2009). Despite these efforts, a knowledge gap remains regarding what drives agricultural intensity change in Europe, especially since the 2000s, when the EU expanded eastwards.

The overall objective of this paper was to improve insights into the spatial patterns as well as drivers and determinants of agricultural intensity changes in the European Union (EU27) between 1990 and 2007. As intensity metrics, we used yields and nitrogen application rates of six crop-type groups from the Common Agricultural Policy Regionalised Impact (CAPRI) Modelling System database. As explanatory factors, we relied on a suite of environmental as well as time-variant demographic and socio-economic variables that are indirect proxies of the underlying drivers of agricultural intensity (hereafter referred to as "spatial determinants"). We understand spatial determinants as driving factors that are spatially associated with agricultural intensity changes in Europe and thus contribute to the statistical explanation of the location and amount of changes (following Meyfroidt, 2015). Our goal was thus to assess changes in the spatio-temporal patterns of two important indicators of agricultural intensity for all of Europe and to describe the spatial determinants that drive these changes using panel regressions. Assessing the influence of actors and underlying drivers of these changes were beyond the scope of this paper.

Specifically, we ask the following research questions:

1. What were the spatiotemporal patterns of yields and nitrogen application in Europe between 1990 and 2007?
2. Which spatial determinants describe these patterns and trends best?
3. How does the importance and relationship of spatial determinants vary between crop-type groups and between agricultural input- and output-intensity metrics?

2. Material and methods

2.1. Agricultural intensity indicators

To assess agricultural intensity across Europe, we used yields and mineral nitrogen application [kg ha^{-1}] (Table 1) from the Common Agricultural Policy Regionalised Impact (CAPRI) Modelling System database (Britz and Witzke, 2014). CAPRI provides the most