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Drivers of changes in agricultural intensity in Europe [1]

Christian Levers [a], Van Butsic [b], Peter H. Verburg [c], Daniel Müller [a,d], Tobias Kuemmerle [a,e]

a Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

b Department of Environmental Science, Policy, & Management, UC Berkeley 130 Mulford Hall #3114, Berkeley, CA 94720, USA

c Environmental Geography Group, Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1087, 1081 Amsterdam, The Netherlands

d Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Theodor-Lieser-Str. 2, 06120 Halle (Saale), Germany

e Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

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Corresponding author:

Christian Levers (christian.levers@geo.hu-berlin.de)

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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 pat- terns 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.

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1 Introduction

Land use has affected more than 75% of the Earth's ice-free sur-face (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 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 crop- land 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 geo- graphic 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 (out- put metric) were strongly associated with higher nitrogen inputs and to a lesser degree to higher precipitation, potential evapo-transpiration, 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

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analyses for understanding pat- terns 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 east- wards.

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 nitro- gen 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 environ- mental 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

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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

This study draws on two concepts that are central to the study of linkages between nature-based surroundings and human well-being: the ecosystem services framework and the cultural values model.

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 Com- mon Agricultural Policy Regionalised Impact (CAPRI) Modelling System database (Britz and Witzke, 2014). CAPRI provides the most comprehensive set of indicators on agricultural management intensity in Europe based on official data from Eurostat, the statistical office of the European Union. We focused on mineral nitrogen application only, as it is the main capital-related input to agricultural areas (EC, 2015a). The CAPRI database provides gap-filled and harmonised information on the management intensity of agricultural areas across Europe that is complemented where needed by national-level data for the most recent member states to extend time series back in time (Britz and Witzke, 2014; c.f. Text S1 in the Supporting information).

We joined the CAPRI data to the respective NUTS (Nomenclature des unités territoriales statistiques, i.e., Nomenclature of Territorial Units for Statistics) regions and calculated annual agricultural intensity indicators for subnational (19 countries) and national (6 countries) administrative units from 1990 to 2007 (Table S1). Since the CAPRI time series currently ends in 2009 for yields and 2007 for nitrogen application, we limited our analysis to the time period 1990–2007. Subnational units represent regions with 3–7 million inhabitants (NUTS1) and 0.8–3 million inhabitants (NUTS2). To consider crop-specific characteristics, we calculated intensity indicators for six crop-type groups separately (see Table S1 for national area coverage), following the stratification of Kempen et al. (2005): cereal crops (soft wheat, durum wheat, rye and meslin, barley, oats, maize, paddy rice, and other cereals), fodder crops (fodder grass, fodder maize, fodder root crops, and other food from arable land), industrial crops (potatoes, sugar beet, textile crops, and other industrial crops), labour-intensive crops (flowers, tobacco, tomatoes, and other vegetables), oilseeds and pulses (rape seed, sun- flower, soya, and pulses), and permanent crops (olives, nurseries, vine, citrus fruits, and other fruits). This decomposition was necessary due to substantial differences in yield and fertiliser application across crop-type groups, and to account for differences between arable land and grasslands. We

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excluded overseas and island NUTS regions not covered by the CAPRI DynaSpat crop-cover database (Common Agricultural Policy Regionalised Impact – The Dynamic and Spatial Dimension; see Section 2.2). This resulted in a total of 220 administrative units that we considered for analysis.

2.2. Explanatory variables

To identify variables that were assumed to influence agricultural intensity patterns, we relied on recent reviews on drivers and determinants of agricultural land-use change (van Vliet et al., 2015a; Hazell and Wood 2008), as well as prior work on agricultural intensity patterns in Europe (Reidsma et al., 2007, 2010, 2009). We hypothesized a relationship between agricultural intensity (i.e., yields and fertiliser use) and each spatial determinant (Table 1). For a detailed description of the variable selection and data sources, see Text S2 in the Supporting information.

We identified 16 potential explanatory variables representing six broad groups: (i) farm characteristics, (ii) micro-economic conditions, (iii) accessibility, (iv) soil conditions, (v) climatic conditions, and (vi) macro-level conditions. Further, we used country and time dummies that account for unobserved differences in countries, such as policies and cultures, and for temporal trends. We aggregated all explanatory variables to the administrative units on which yields and fertiliser input were reported (NUTS0 to NUTS2, see Section 2.1). To do so, we first re-projected all raster data into the Lambert Azimuthal Equal Area projection and, if necessary, resampled them to a 1 1 km2 grid using bilinear resampling for all continuous and nearest neighbour resampling for all categorical variables. Subsequently, we aggregated raster variables for each administrative unit using a weighting approach that considered the spatial coverage of each crop-type group. To do so, we multiplied each raster with a continuously-scaled raster representing the spatial coverage of each crop-type group (CAPRI-DynaSpat at 1-km resolution for the year 2000; Leip et al., 2008). This procedure was necessary because our goal was to describe the variability of conditions within areas covered by a specific crop-type group, which can be small for a given administrative unit, and not to describe the general conditions of an administrative unit.

2.3. Regression analyses

Regression models are powerful tools to assess the drivers and determinants of changing land-use patterns (Levers et al., 2014; Müller et al., 2013). Panel regressions are particularly well-suited to do so as they can control for latent time-invariant, unobserved heterogeneity (i.e., omitted explanatory variables). This is a major advantage for land-use assessments because consistent measurements across time and space are often lacking for potentially important explanatory variables. We used random effects panel regressions to relate our two agricultural intensity indicators to the explanatory variables (Table 1).

Random effects models are highly suitable to investigate phenomena that change over time. Often, these data sets are unbalanced due to considerable variation in number and timing of observations and the uncontrollability of the circumstances under which measurements were taken, restricting the use of traditional multiple linear regressions (Laird and Ware, 1982). Random effects models assume that the time-invariant, unobserved heterogeneity (i.e., the error term) is uncorrelated with the explanatory variables and hence treated as a random variable in the model, in contrast to fixed effects models where it is treated as a parameter (Gardiner et al.,

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2009). Furthermore, random effects models allow for an explicit analysis of between- and within-variations among observations (Laird and Ware, 1982).

Before running our panel regressions, we merged and harmonised target and explanatory variables. As some explanatory variables were not available as annual time series (see Table 1), we used the time steps 1990, 1993, 1995, 1997, 2000, 2003, 2005, and 2007. Subsequently, we checked for missing years in the target datasets and excluded regions with data in less than half of the time steps, or missing data in three or more consecutive time steps. We filled remaining data gaps (1.6% and 4% of all observations across crop-type groups for yields and nitrogen application, respectively) either by interpolation or by using the first or last value of the study period in cases where gaps occurred at the beginning or end of the study period. Random effects models require that variables have values for all observations for at least one time step. Since not all explanatory variables satisfied this requirement, we had to exclude Belgium (10 observations), Slovenia (1 observation), and Spain (16 observations) from the regression analysis. Our final dataset contained 164 (oilseeds and pulses), 173 (labour-intensive crops), 176 (permanent crops), and 178 (cereal, fodder, and industrial crops) observations.

We checked for non-linearity between explanatory variables and targets, and included explanatory variables with a non-linear relationship as linear and centred quadratic terms. We calculated Spearman p values between all explanatory variables (Table S2) to investigate possible collinearity. We excluded the explanatory variable with a weaker correlation with the target variable from variable pairs where p exceeded 0.8 (Booth et al., 1994).

We set up separate models for yields and fertiliser application per crop-type group, resulting in a total of twelve models. Model performances were estimated using overall R2 values. We used panel model z-values to assess the importance of each explanatory variable within our models, robust standard errors to deal with possible heteroscedasticity, and Moran's I (Moran, 1950) to assess spatial autocorrelation of residuals. We considered an explanatory variable as significant if its p-value was below 0.1. We calculated marginal effects for each explanatory variable and created predicted margin plots at ten quantiles (5% to 95% quantile in 10% intervals) to describe the form and direction of the relationship between target and explanatory variables along their data range.

All analyses were performed with the xtreg command in STATA (StataCorp, 2013) and all post-processing was done in R (R Core Team, 2014).

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3 Results and interpretation

3.1. Country-level patterns of agricultural intensity in Europe

Between 1990 and 2007, EU-wide yields for all six crop-type groups combined increased by approximately 10% (Fig. 1, left panel) corresponding to a mean annual increase of 0.58% (s.d. = 2.27%). Industrial and labour-intensive crop yields increased most strongly (by 21.25% and 37.95%, respectively), and revealed the highest yields among all crop-type groups we explored. Yields from fodder crops (14.65%) and permanent crops (12.50%) increased to a lesser degree, whereas yields for cereal crops (3.68%) as well as for oilseeds and pulses (2.56%) remained fairly stable with the lowest yield levels of all crop-type groups.

However, yield trends for each country and crop-type group did not always follow EU-wide trends (Fig. S1). For example, in some countries overall crop yields were stable (e.g., Netherlands or Den- mark) or even declining (e.g., Bulgaria or Poland) over the study period.

Similarly, industrial and labour-intensive crops did not consistently show the strongest increases (e.g., Ireland or Belgium) and even declined (e.g., Finland or Sweden). Among crop-type groups, yield levels were largely in line with EU-wide patterns with a few exceptions (e.g., highest yields for permanent crops in the Nether- lands and Belgium or high fodder yields in Ireland and Latvia). Generally, yields across crop-type groups were generally higher and showed clearer increasing trends in Western European countries, especially in the EU15 countries, compared to countries in Europe’s east, which even had decreasing yields.

Mineral nitrogen application in the EU decreased by about 10% for all six crop-type groups combined (Fig. 1, right panel) with a mean annual decrease of 0.63% (s.d. = 2.61%). After a marked decrease in the early 1990s, nitrogen application levels increased in the late 1990s followed again by a monotonic decrease after 2000. This trend was observable for all crop-type groups, except for oilseeds and pulses that experienced a steady increase after the mid-1990s (15.96%). Fodder crops had the strongest decrease (27.61%) followed by permanent crops (5.62%), both having the comparably lowest nitrogen application rates we explored. Nitro- gen application for cereal, labour-intensive, and industrial crops remained approximately stable (3.83% to 0.06%) but had the highest application levels observed.

Nitrogen application rates also showed characteristic trends for each country and crop-type group (Fig. S2). For example, in some countries total nitrogen application was approximately stable (e.g., Sweden or Spain) or even increasing, sometimes strongly (e.g., Poland or Slovakia), contrary to EU-wide trends. Also, temporal dynamics of fodder crops (e.g., Belgium or Sweden) and oilseeds and pulses (e.g., Czech Republic) were highly variable and deviated from the overall strong decreases (fodder) or increases (oilseeds and pulses). Among crop-type groups, nitrogen application levels were largely in line with EU-wide patterns. Generally, nitrogen application rates across crop-type groups were higher in Western European countries compared to countries in Europe’s east. How- ever, Western and Central European countries generally showed decreasing nitrogen application rates in contrast to Eastern European countries, where nitrogen application was often increasing during our study period, though not reaching the levels of Western and Central Europe.

3.2. Subnational patterns of agricultural intensity in Europe

Overlaying subnational patterns of yields and nitrogen application confirmed the general, country-level pattern of high agricultural intensity across all six crop-type groups in Western and Central Europe, compared to lower-intensity in the remainder, especially in Eastern Europe (Fig. 2a). However, subnational variation was evident for each crop-type group and intensity indicator. Regions with values above EU-average for both intensity indicators were rare and occurred, for example, in Northern France and Germany (cereal crops) or in the Netherlands and Northern Sweden (labour-intensive crops). Generally though, regions were characterised by one dominant above-average intensity indicator, for example for yields in South-Western France and Northern Italy (cereal crops, oilseeds and pulses) and parts of Northern Germany, Italy, and France (industrial crops) or for nitrogen application rates in Northern Sweden and Finland (fodder crops) and Southern Germany and Northern UK (oilseeds and pulses).

Temporal variation of yields and fertiliser application over the study period also exhibited marked subnational differences (Fig. 2b). Above-average variability for nitrogen application occurred in North-Western France, the eastern part of the Nether- lands, and for large parts of Bulgaria and Greece (cereal crops) or the UK, central parts of the Netherlands, Western Germany, and much of Eastern European countries (labour-intensive crops). In general, we

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found a stronger subnational variability in nitrogen application compared to yields variability. Strikingly, above-average yield variability was particularly evident in regions of Southern and Northern Europe (except for fodder and permanent crops in Finland), while the remainder was to a greater extent characterised by above- average variability in nitrogen application.

Yield-nitrogen ratios relate agricultural output to input intensity. Increasing ratios indicate a divergent trend between yield and fertiliser levels and consequently an elevated efficiency of fertiliser use that can be the result of several pathways (e.g. higher yields at stable fertiliser application, stable yields at lower fertiliser application, etc.). Diverging Europe-wide yield and fertiliser application trends (see Section 3.1) pertained at sub-national level (Fig. 3). Over the study period, the ratio between applied nitrogen fertiliser and obtained yields (both in kg ha^{-1}) increased for all six crop-type groups, most notably for industrial, labour-intensive, and permanent crops.

3.3. Spatial determinants of changes in agricultural intensity in Europe

The explanatory power of the six crop-type group models for yields ranged from R2 = 0.66 for industrial and labour-intensive crops to R2 = 0.94 for permanent crops. Explanatory power was somewhat lower for nitrogen application models, ranging from R2 = 0.47 for industrial crops to R2 = 0.68 for cereal crops (Table 2). Residuals were mostly normally distributed, except for fodder and permanent crops that had a slightly skewed and leptokurtic distribution (Figs. S3 and S4). We found low levels of spatial autocorrelation within model residuals (Griffith, 2009) for yields (I = 0.14–0.28) and for nitrogen application rates (I = 0.19–0.39), except for permanent crop yields (I = 0.70). We found no signs of temporal autocorrelation in the model residuals, both for yields and nitrogen application rates (Table S3, Figs. S5 and S6). Time was an insignificant predictor for yields and nitrogen application rates and no clear temporal trends were observed in the residuals.

Depending on the crop-type group, different explanatory variables were important (Table 2; detailed results in Tables S4 and S5). Variables from all groups showed significant effects on yields for cereals as well as oilseeds and pulses, whereas fodder yields were mainly characterised by micro-economic conditions. Farm characteristics, climatic, soil, and micro-economic conditions were the most dominant factors for describing industrial crop yields, similar to labour-intensive and permanent crop yields. Across all crop-type groups, seven explanatory variables were significantly related to yields in at least half of the models (Table 2 and Fig. 4).

Higher nitrogen application rates generally affected crop yields positively, with the highest leverage effect for fodder and permanent crops. Higher crop specialisation (croparea uaar) was positively related to yields from labour-intensive crops and oilseeds and pulses, while the remaining crop-type groups showed decreasing or stable yields with increasing crop coverage per utilised agricultural area. Higher labour productivity (fnv awu) was generally positively related to yields, except for fodder and permanent crops. Soil water availability (swap) was positively related to crop yields for cereal and industrial crops, as well as for oilseeds and pulses but negatively related to the remaining crop-type groups. Annual precipitation sums (prcp sum year) revealed a generally positive effect on crop yields while our results showed that growing degree days (gdd) had a negative, though generally marginal, effect on crop yields, especially for industrial crops.

Overall, predicted yield margins were consistently lowest for cereal crops as well as oilseeds and pulses, while labour-intensive and industrial crop yields were highest. Cereal crops, as well

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as oilseeds and pulses, also showed the lowest absolute variability for predicted yield margins, while the other crop-type groups showed high variability for certain explanatory variables. Country- specific effects on yields were evident for permanent crops with high yields especially for the Netherlands and UK, and to a lesser degree for industrial crops (Denmark, Italy, and Portugal) and labour-intensive crops (Austria, Germany, and the Netherlands).

Time-dependent effects showed increasing yields over time particularly for industrial, fodder, labour-intensive, and permanent crops whereas time did not reveal any effect on yields for cereals and oilseeds and pulses (Fig. S7).

Compared to yields, we found fewer variables to be significant for describing nitrogen application rates. For cereal, fodder, industrial, and permanent crops, significant variables were climatic, soil, and micro-economic conditions. Farm characteristics, micro-economic and climatic conditions, and accessibility were important for labour-intensive crops, while nitrogen application rates for oilseeds and pulses were determined by farm characteristics as well as micro-economic and soil conditions. Across all crop-type groups, five explanatory variables were significantly related to nitrogen application in at least half of the models (Table 2 and Fig. 5).

Larger fields (field size) were generally positively related to nitrogen application rates, except for permanent crops. Higher crop specialisation (croparea arable) was positively related to nitrogen application rates especially for labour-intensive crops and oilseeds and pulses, but also to industrial and cereal crops. Labour productivity (fnv awu) had a consistently positive effect on nitrogen application, except for permanent crops. Growing degree days (gdd) revealed no uniform effect, affecting nitrogen application rates for labour-intensive crops positively, but negatively for cereal and permanent crops. Soil organic carbon content (soc topsoil tc) was positively related to nitrogen application for four crop-type groups (cereal, fodder, and permanent crops and oilseeds and pulses). Higher soil water availability (swap) was generally related to higher nitrogen application rates, especially for cereal, fodder, and industrial crops.

Predicted nitrogen application rate margins were consistently lowest for fodder and permanent crops and highest for cereal, industrial, and labour-intensive crops. Absolute variability for predicted nitrogen application margins varied strongly according to the explanatory variable and crop-type group. Country-specific effects on nitrogen application rates revealed distinct patterns for each crop-type group (Fig. S8). High values were predicted for permanent crops (esp. Denmark, Finland, Netherlands), labour- intensive crops (esp. Denmark, Ireland, Netherlands), and industrial crops (esp. Italy and Netherlands).

4. Discussion

Shifting to more sustainable agriculture in light of the grow- ing demands for agricultural products is a grand challenge. Better understanding where and why agricultural intensity patterns change is important in this context in order to identify trade- offs between agriculture and the environment as well as to find pathways for sustainable intensification. We mapped sub-national changes in yields and nitrogen application for six broad crop-type groups across the European Union between 1990 and 2007 and quantified their spatial determinants. Five main conclusions arise from our analyses, which we discuss in more detail:

1. Crop yields increased across Europe in our study period, however with diverging trends among crop-type groups. These differences are likely the result of changes in agricultural policies, commodity prices, as well as climate change.

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2. Nitrogen application rates decreased over much of Europe, likely due to changes in policies (e.g., Nitrate Directive), the breakdown of socialism, and changes in nitrogen use efficiency.

3. Regions of high input and output intensity were similar across crop-type groups, and mainly located in Western and Central Europe. Lower intensity prevailed in Eastern Europe, mirroring the legacies from the breakdown of socialism.

4. Diverging EU-wide yield and nitrogen application trends suggest a decoupling of output from input intensity, and thus increasing nitrogen use efficiency, related to improvements in land-management.

5. Temperature was negatively related to crop yields, likely because we focussed on the actual area covered by each crop-type group and suggesting that GDD increases would not increase suitability of agricultural areas under management.

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4.1. Patterns and trends of agricultural-intensity change

Generally, crop yields increased modestly during our study period, in line with the documented levelling off of cropland productivity in Europe towards the late 20th century (Gingrich et al., 2015). Yields from cereals as well as oilseeds and pulses remained stagnant in the EU27 since the early to mid-1990s, while industrial and labour-intensive crop yields increased strongly in this period. Three factors explain these trends. First, agricultural policy changes, especially stricter EU-wide and national environmental protection since the early 1990s (e.g., through agri-environment schemes and cross-compliance) and the decoupling of Common Agricultural Pol- icy (CAP) subsidies from agricultural production, likely translated into stagnating or declining cereal production (Balkhausen et al., 2008; Schmid and Sinabell 2007). Second, long-term warming negatively affected yields for wheat and barley (i.e., cereal crops), but allowed for yield increases for sugar beet (i.e., industrial crops) in Europe (Moore and Lobell, 2015). Finally, biophysical limits to yields are likely approached in Europe (Peltonen-Sainio et al., 2015; Moore and Lobell 2015), i.e., the potential yield, determined by soil type, climate, crop properties, and available water, is attained (Penning de Vries et al., 1995).

The overall decrease in mineral nitrogen application rates for the majority of EU27 countries is, also quantitatively, in line with other findings, as are the increasing or recovering trends we found for some countries (e.g., in the Czech Republic or Poland (EC 2015a; Sutton et al., 2011)). In Western Europe (i.e., EU15), the decrease is likely the result of the Nitrates Directive of the European Com- mission in 1991 (Council of the European Union, 1991) as well as of the implementation of national agrinvironment programmes (Peltonen-Sainio et al., 2015) that aimed at lowering nitrate pollution of water bodies. In Eastern Europe, in contrast, the institutional and economic transition following the breakdown of socialism (EC, 2015a) resulted in lower support for farming and higher fertiliser prices, which led to a substantial decline in capital-intensive farming practices (Rozelle and Swinnen, 2004). Nitrogen use efficiency also increased in the European countries within our study period (Lassaletta et al., 2014), which fits to the observed decreases in nitrogen application we found.

Our analyses revealed a strong east-west divide in the spatial patterns of agricultural intensity in Europe (Fig. 2). The concentration of high-intensity agricultural systems in Western and Central Europe contrasts with mostly low-intensity systems in the peripheries of the EU27 and confirms findings for yields from cereals, oilseeds and pulses, and industrial crops (Supit et al., 2010) and for nitrogen application on arable land (Temme and Verburg 2011; Overmars et al., 2014). This pattern may represent land-use legacies as Western and Central European agriculture shifted to regions with higher potential productivity in the last century (Bakker et al., 2011). These productive agricultural regions are characterised by an early industrialisation of agricultural land use and a quick adoption of technologies (Jepsen et al., 2015) as well as lower yield gaps (Neumann et al., 2010), while marginal areas experienced low-intensity land-use or even de-intensification (Kuemmerle et al., 2015; Meyfroidt and Lambin, 2011). Furthermore, structural changes in agriculture and the economic challenges faced by agricultural enterprises in the early post-socialist period, have led to drastic declines in harvested areas and yields in many former Socialist countries (Rozelle and Swinnen, 2004), further explaining the east-west divide we observed.

Our results suggest increasing yields and decreasing nitrogen application rates for the EU27 over the last almost 20 years, thus implying a decoupling of yields from nitrogen input. As European environmental policies and regulations resulted in a reduction of total nitrogen inputs to agriculture (van Grinsven et al., 2012; Jepsen et al., 2015), our study suggests yields increased mainly due to a better nitrogen management (Lassaletta et al., 2014). Another explanation for the divergent yield and nitrogen application trends might be the polarisation of land uses (i.e., concentration of agricultural production in fertile areas via intensification while marginal areas are abandoned) that resulted in production increasingly being carried out by large-scale, market-oriented farms, possibly more efficient nitrogen application (Jepsen et al., 2015).

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4.2. Spatial determinants of agricultural-intensity change

The strong positive influence of mineral nitrogen application on yields across all crop-type groups is not surprising as mineral nitrogen is an essential nutrient for crop growth and often the limiting factor for yields (Lobell, 2007). Interestingly, the relationship between nitrogen application and yields from oilseeds and pulses was significantly negative. Contrary to prior findings for yields of selected cereal and industrial crops (Reidsma et al., 2007), temperature was negatively related to crop yields in our analysis. A possible explanation is that country- and time-related differences, explicitly included in our analysis, controlled for temporal and latitudinal climate differences that drive yield pattern (higher yields in temperate zones compared to drier and warmer Southern and moister and colder Northern parts of Europe). Furthermore, we focussed on the actual area under each crop-type group, thus avoiding bias where aggregation units are environmentally diverse but include only a small area of agriculture (e.g. in mountain areas). This may explain the surprising result of a negative sign for GDD, as our models did not characterise agricultural conditions in contrast to non-agricultural sites (where a positive sign can be expected at the European scale), but focussed on agricultural areas only. Given Europe’s long land-use history and the concentration of agriculture on productive sites since the 19th century (Jepsen et al., 2015), most agricultural areas under management can be assumed to be in favourable conditions, and further GDD increases would thus not increase suitability and consequently crop production and yields. The positive relationship between yields and higher water availability for plants we found (both regarding precipitation and soil water content) is intuitive, as soil water availability positively affects nitrogen fertilisation and thus plant growth (Morell et al., 2011). Finally, the positive relationship between higher labour productivity (net value added per annual working unit) and yields indicates that higher income provides a higher capital stock, which may translate into higher yields via increased input applications (e.g., through fertilisers, plant protection, high-yielding crop varities, or mechanisation) (Alston and Pardey, 2014).

We found higher nitrogen application rates where soil organic carbon contents were high. Low soil carbon-to-nitrogen ratios (<25) are preferable for nitrogen uptake, since mineralisation leads to excess nitrogen in the soil that can be taken up by plants (Chapin et al., 2012). Also, soil water availability is positively related to nitro- gen application (Abreu et al., 1993). Locations with higher economic performance had higher nitrogen application rates since farms in such regions likely have more purchasing power to afford buying fertiliser (Alston and Pardey, 2014). Population density played a minor role in describing yield and nitrogen trends, in line with case-study evidence suggesting a growing disconnect of population trends and agricultural development due to urbanisation and the globalisation of agricultural markets (van Vliet et al., 2015a; Meyfroidt et al., 2013).

4.3. Model performance, uncertainties, and data constraints

Our panel regression approach resulted in plausible response curves and high models fits. Remaining uncertainty is due to data constraints that reduced model performance. First, the low temporal resolution of some variables forced us to limit the analyses to coarse time steps that masked annual fluctuations in yields or nitro- gen application rates. Moreover, we could not include irrigation in our final analyses because of its low temporal and spatial coverage that would have resulted in a substantial reduction in the number of observations. As crop yields are sensitive to water deficits (Steduto et al., 2012), incorporating irrigation in our models would have been particularly important in regions where it could alleviate water stress, such as the Mediterranean. Despite data constraints, we ran alternative models including irrigation for the limited number of observations (130–144 NUTS regions) to test its influence on yields and nitrogen application. Results (not shown) revealed a significant effect of irrigation on yields for labour-intensive and permanent crops and on nitrogen application for fodder crops while signs and loadings of the remaining explanatory variables remained akin. Due to the lack of data, we could also not incorporate changes in soil organic carbon or water contents, although they may influence fertiliser application and hence crop yields. Moreover, we could not include important pan-European political, regulatory, or institutional changes that arguably influenced agriculture (see Table S6) due to their lack of spatial variation. For example, the overall decrease in mineral nitrogen application rates observed in our study period was likely also related to the Nitrates Directive of the European Commission in 1991 and the decoupling of CAP subsidy payments from production goals.

Second, by considering multiple crop varieties and categorising them into crop-type groups of similar characteristics, we incorporated more information compared to assessing single crop varieties. However, this came at the expense of identifying crop-specific phenomena. Third, we used the reported wet-weight yield data to calculate yield-nitrogen ratios. As water content differs substantially between crops, the resulting efficiency ratios may be biased. Conversion factors to dry-weight units are not available for all crop types used in our analyses but would allow for a better comparison of yield-nitrogen ratios between crop-type groups. Finally, other indicators capture different aspects of management intensity in agricultural areas (e.g., phosphorus or pesticide application, number of tractors, or livestock density; Kuemmerle et al., 2013) and would provide a richer picture of the intensity of agricultural systems, but data on these metrics are lacking or, if existent, have strong spatial or temporal limitations (e.g., Tóth et al., 2014 for phosphorus application).

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5 Conclusion

Better understanding the spatial patterns and drivers of agricultural intensity changes is an important prerequisite for designing policy tools for shifting to more sustainable agricultural modes. Against this background, a number of management implications arise from our study.

First, although yields were strongly related to nitrogen application, predicted yield margins suggested that higher nitrogen input did not result in substantial yield increases (see Lassaletta et al., 2014). Considering the diminishing returns of increasing fertiliser application (Tilman et al., 2002) and negative environmental effects of nitrogen fertilisation, such as nitrate leaching or impact on global warming potential (Erisman et al., 2011), the gains from increasing fertiliser use might thus be limited in large parts of Europe. Second, soil quality (carbon and water content) was an important indicator for agricultural intensity in our analyses. To maintain functioning agricultural production systems, apt soil management measures are required in order to prevent soil degradation that could harm future agricultural production (Tilman et al., 2002).

Third, micro-economic settings were generally influential in describing agricultural intensity patterns. Whereas biophysical factors typically respond rather slowly to interventions, policies can affect micro-economic conditions quickly, for example via the CAP Pillar II rural development mechanisms, providing opportunities for steering land systems towards desired pathways. Fourth, our results highlight the benefits of jointly analysing input and output intensity since focussing only on a single intensity metric may lead to misjudgements in regard to an agricultural system’s intensity. Furthermore, our study underpins the potential of panel regression models to investigate land-use change phenomena and the power of margins plots to communicate these results.

Finally, the outcomes of our analyses offer valuable inputs for identifying pathways for a more sustainable future land use in Europe. We provide starting points for regionalised and spatially targeted policy solutions by considering national and subnational differences that can result in specific policy requirements for agriculture (see Gorton et al., 2009), the identification of candidate regions for intensification or dis-intensification, or the evaluation of potential benefits and trade-offs of specific land-use strategies. For example, identifying areas of high agricultural intensity (e.g., areas with excess nitrogen application) could be targeted with strategies to reduce nitrogen application and hence land-use pressure. Like- wise, in areas with currently low- to medium-intensive agriculture policy makers may focus on strategies to sustainably intensify agriculture, but this is challenging given the substantial conservation values that some of these landscapes have (Kleijn et al., 2009; Bignal and McCracken 1996). Further, the outcomes of our analyses can serve as inputs for multi-criteria and trade-off analyses that seek to create synergies between agricultural production and environmental protection (Macchi et al., 2015; Phalan et al., 2011) in order to identify pathways for sustainably intensifying agricultural areas in Europe.

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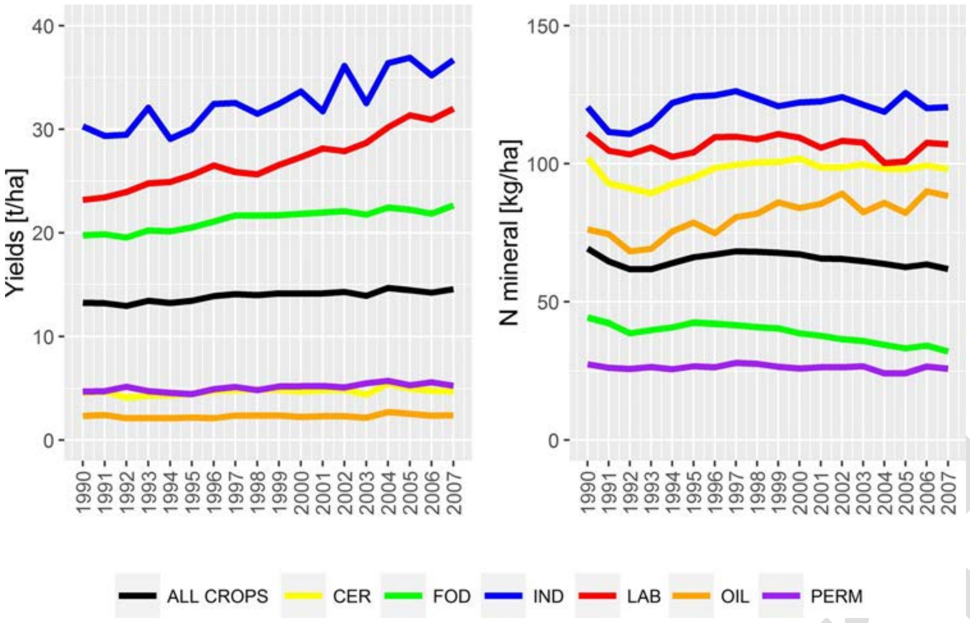

Figure 1.

Time series of yields [t ha−1] (left panel) and mineral nitrogen application [kg ha−1] (right panel) for six crop-type groups individually and combined for the EU between 1990 and 2007. Crop-type groups are cereal crops (CER), fodder crops (FOD), industrial crops (IND), labour-intensive crops (IND), oilseeds and pulses (OIL), and permanent crops (PERM) and their aggregate total (ALL CROPS).

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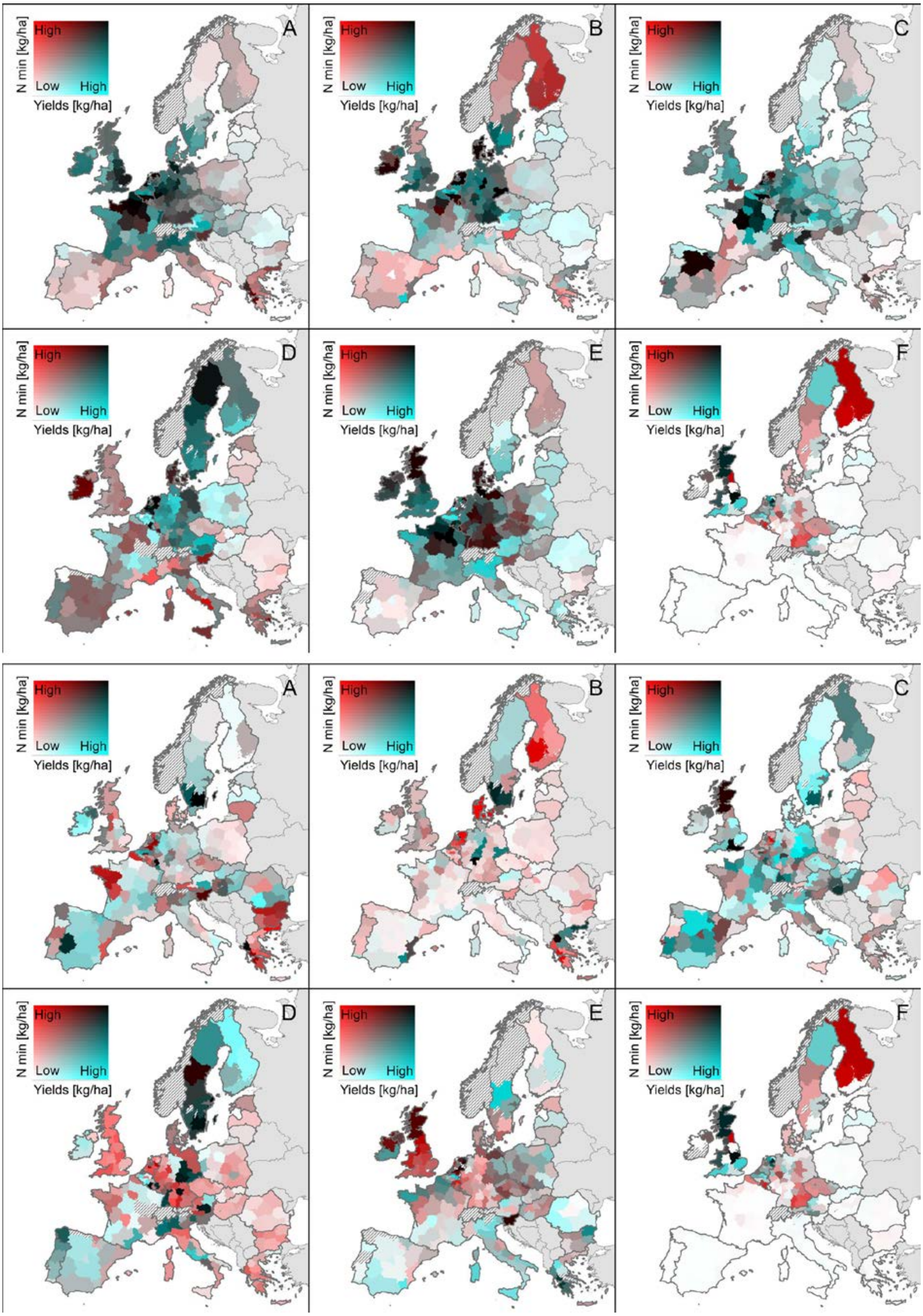
High
N min [kg/ha]
Low
High
Yields [kg/ha]
A
High
N min [kg/ha]
Low
High
Yields [kg/ha]
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N min [kg/ha]
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High
Yields [kg/ha]
C
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N min [kg/ha]
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Yields [kg/ha]
F

Figure 2.

Concordance maps of mean values (2a) and standard deviations (2b) of yields [kg ha−1] and fertiliser application [kg ha−1] for cereals (panel A), fodder crops (panel B), industrial crops (panel C), labour-intensive crops (panel D), oilseeds and pulses (panel E), and permanent crops (panel F) between 1990 and 2007. Values were z-transformed. Bright blue colours indicate high mean/sd for yields, bright red colours indicate high mean/sd for fertiliser application, white and black colours indicate low and high mean/sd, respectively, for both variables. Hatched areas represent NUTS regions that were excluded from the analysis due to data gaps.

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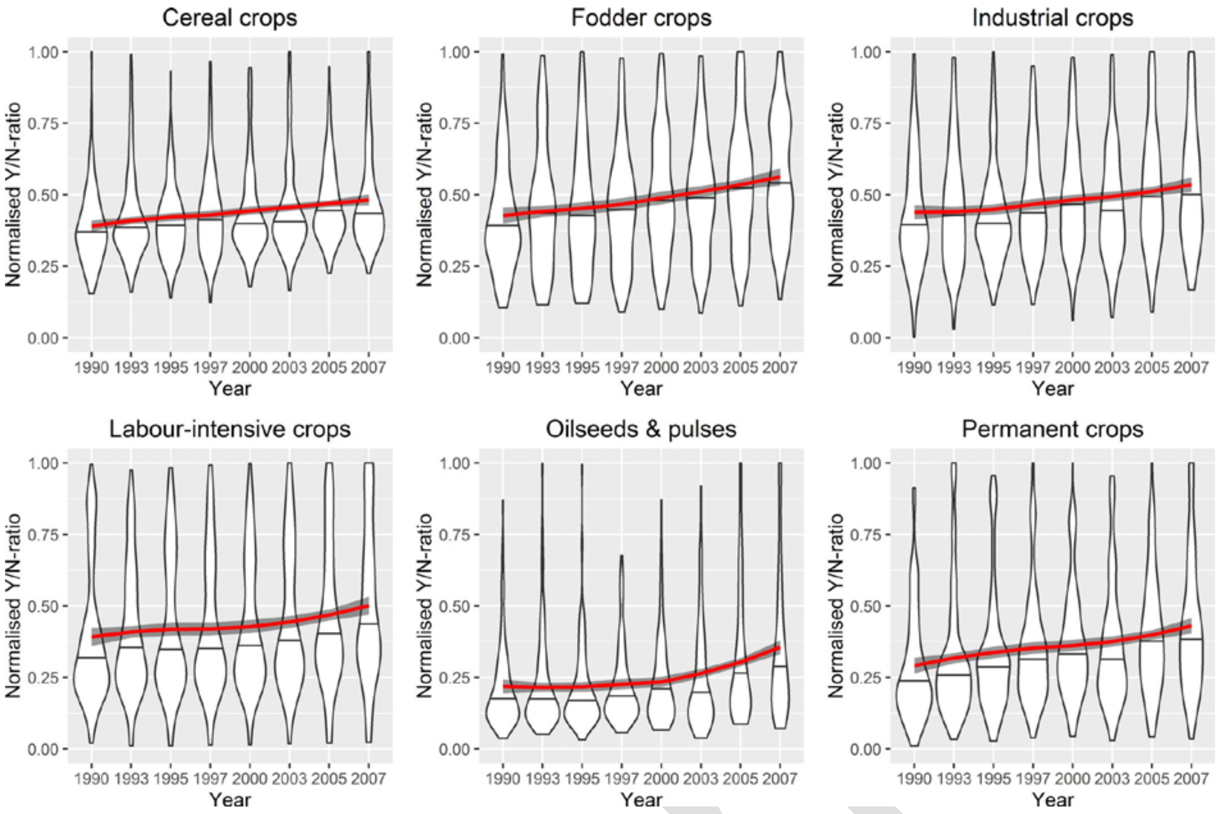

Figure 3.

Violin plots of yield-nitrogen ratios for all six crop-type groups for each time step of the analysis between 1990 and 2007. The shape of each plot resembles the underlying data distribution (i.e., density). Horizontal lines indicate the respective median and the plots show a loess-smoothed trend line (red line) and corresponding standard errors (dark grey envelope). To exclude outliers, we capped values at the 95th percentile for all crop-type groups (except for fodder crops, for which we used the 80th percentile). We normalised the data between 0 and 1 to be able to compare the temporal trends among crop-type groups.

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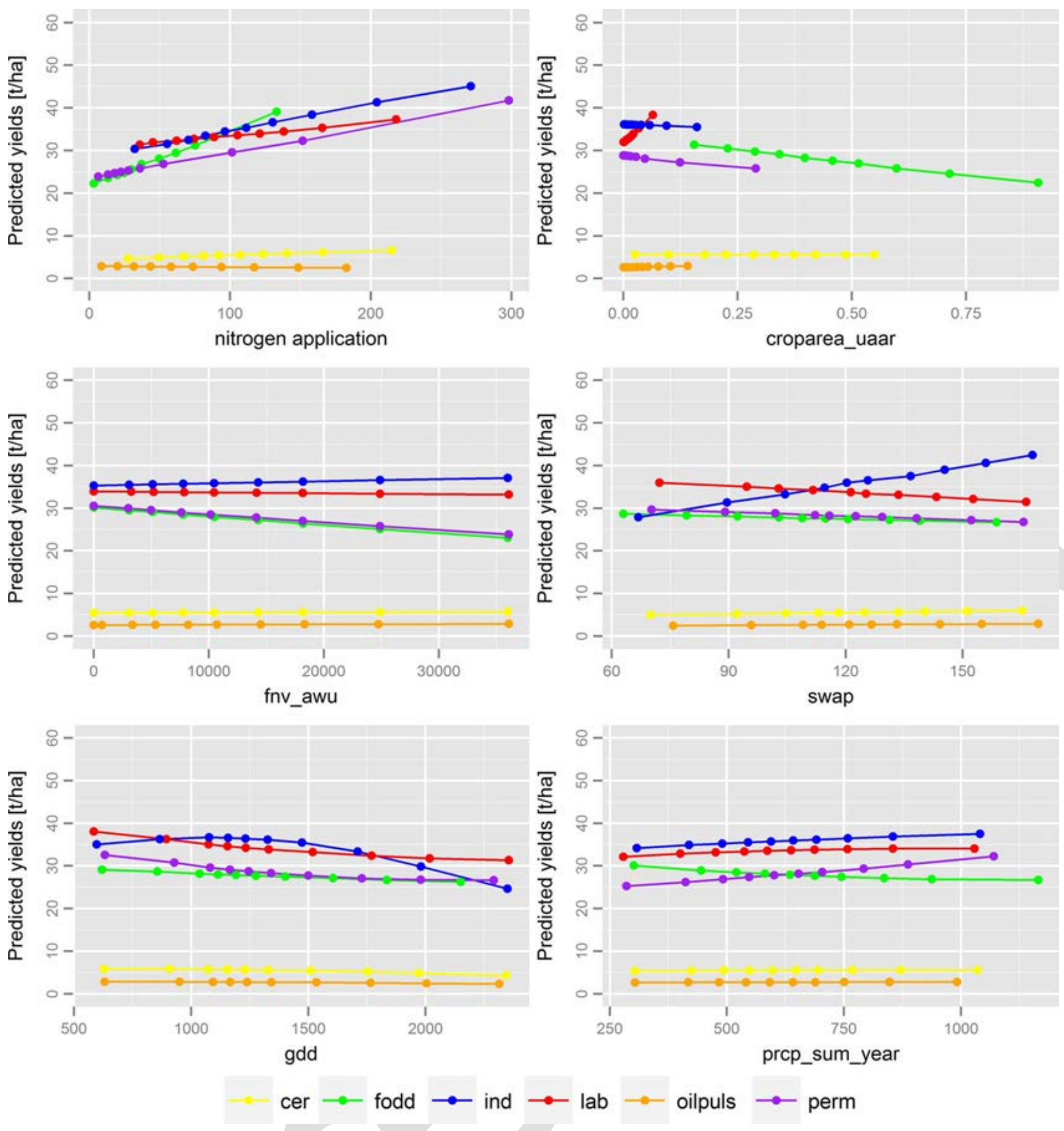

Figure 4.

Predicted margin plots for yields [t ha−1] for all six crop-type groups for the most important explanatory variables (terrain ruggedness was excluded): applied nitrogen, crop-area per utilised agricultural area, economic performance, soil water availability, growing degree days, and annual precipitation sums.

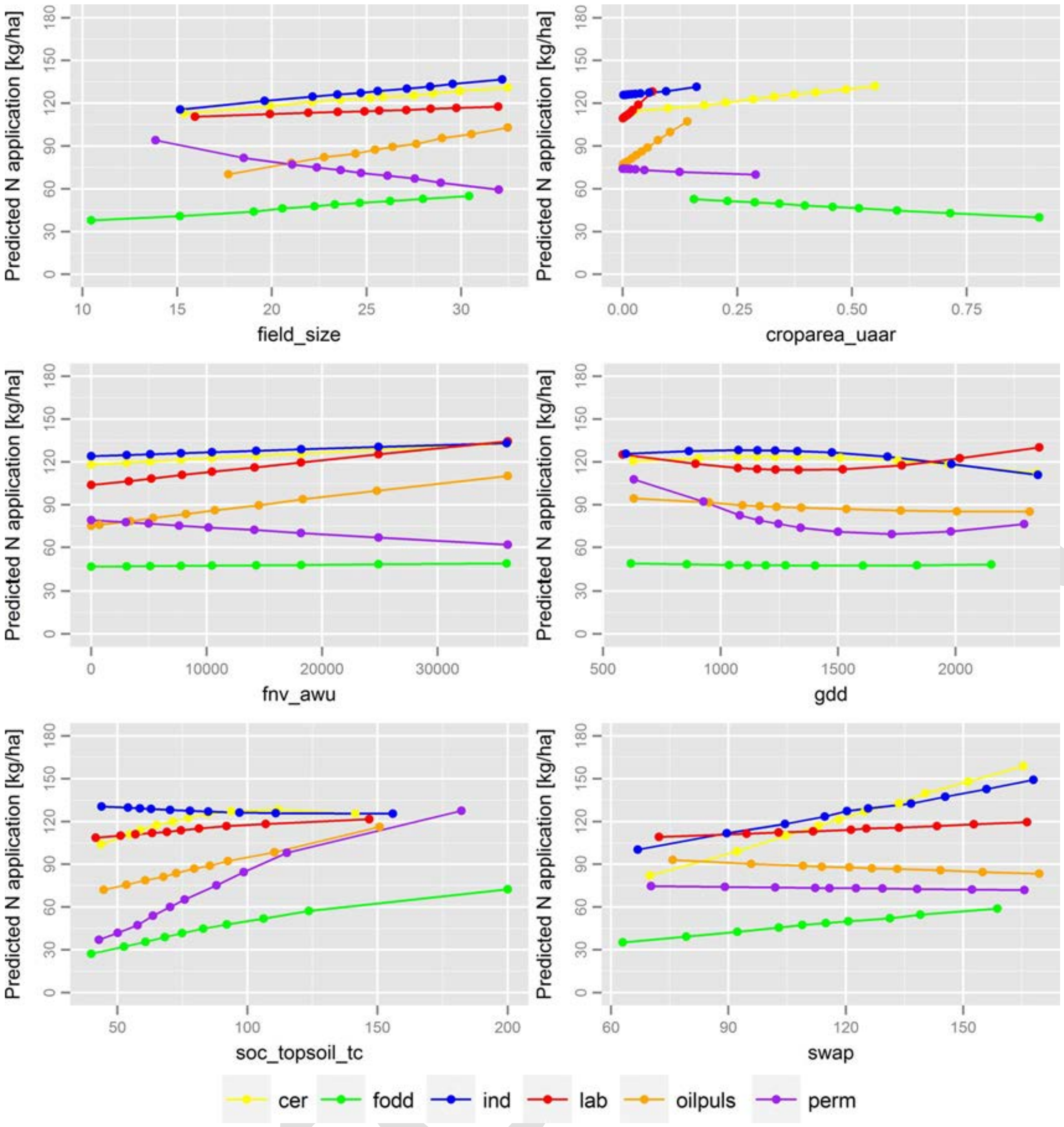

Figure 5.

Predicted margin plots for mineral nitrogen application [kg ha−1] for all six crop-type groups for the most important explanatory variables (economic performance was included): field size, crop-area per utilised agricultural area, economic performance, growing degree days, soil organic carbon, and soil water availability.

Table 1.

Overview of target and explanatory variables and their descriptive statistics. Explanatory variables marked with an asterisk were included as linear and quadratic terms in the regression model. Expected directions of influence are separated for yields (first sign) and nitrogen application (second sign). Some explanatory variables were only available for selected years (in the table referred to as 8 panels): 1990, 1993, 1995, 1997, 2000, 2003, 2005, and 2007.

Group	Variable name	Description	Unit	Year	Source	Sign	Format	Res
Target	yields	CAPRI crop production per area	kg ha^{-1}	1990–2009	Britz and Witzke, 2014	•	V,D	•
	nitrogen (mineral) application	CAPRI application of mineral nitrogen fertiliser per area	kg ha^{-1}	1990–2007	Britz and Witzke, 2014	•	V,D	•
Farm and farmer characteristics	field_size	Interpolation of field size categories ranging from 10 (very small) to 40 (large)	•	•	Fritz et al., 2015	+|+	R,S	1 km^2
	sgm	Annual working units (i.e., one person working full-time)	#	8 panels	EC, 2015b	−|-	V,D	•
	holdings_uaar	Number of holdings per utilised agricultural area	# ha^{-1}	8 panels	EC, 2015b	−|-	V,D	•
	croparea_uaar	Area share of crop-type groups from total utilised agricultural area	%	8 panels	EC, 2015b	+|+	V,D	•
Micro-ecomomy	fert_uaar	Expenses for fertilisers per utilised agricultural area	€ ha^{-1}	8 panels	EC, 2015b	+|+	V,D	•
	fnv_awu	Labour productivity (ratio of farm net value added and labour input)	€ awu^{-1}	8 panels	EC, 2015b	+|+	V,D	•
Access	acc50*	Travel time to	min	2000	Nelson, 2000	−|-	R,S	1 km^2

Group	Variable name	Description	Unit	Year	Source	Sign	Format	Res
		cities > 50,000 inhabitants						
	rugg	Terrain ruggedness expressing relief energy	m	2000	Own calculation, Jarvis et al., 2008 and Riley et al., 1999	−|-	R,S	1 km^{2}
Soil	soil_pH	Soil pH values	•	2006	Panagos et al., 2012 and EC, 2010	•	R,S	1 km^{2}
	soc_topsoil_tc*	Soil organic carbon stock in agricultural soils in 0–30 cm soil depth	tC ha^{-1}	2010	Lugato et al., 2014a, Lugato et al., 2014b and Panagos et al., 2012	+|+	R,S	1 km^{2}
	swap	Soil water availability for plants	mm	2006	EC, 2006	+|+	R,S	1 km^{2}
Climate	gdd*	Growing degree days (calculated based on daily mean temperatures with 10 °C as base temperature)	#	8 panels	Haylock et al., 2008	−|-	R,D	0.25°
	prcp_sum_year*	Annual precipitation sum	mm	8 panels	Haylock et al., 2008	+|+	R,D	0.25°
Macro-level & dummy variables	popdens*	Population density	pers km^{-2}	8 panels	EC, 2015b	−|-	V,D	•
	country	Country dummy to capture country specific information (enumeration from north to south)	•	•	Own specification	•	V,S	•
	time	Time dummy to capture time-step specific information	•	•	Own specification	•	V,S	

Table 2.

Model fit and variable importance for all models. All explanatory variables with p-values < 0.1 were selected. Plus (+) signs indicate a positive effect on the target variable, minus (−) signs a negative effect. Explanatory variables that entered the model as linear and quadratic term are marked with asterisks and signs are provided for both linear and quadratic terms, with insignificant terms in parentheses. Detailed information on panel model regression coefficients, standard errors, and significance levels are provided in Tables S2 and S3 in the SI.

Summary		Yields						Nitrogen					
		cer	*fodd*	*ind*	*lab*	*oil*	*perm*	*cer*	*fodd*	*ind*	*lab*	*oil*	*perm*
FIT	overall R^2	0.79	0.79	0.66	0.66	0.72	0.94	0.68	0.66	0.47	0.61	0.58	0.58
	observations	957	957	956	902	868	940	957	957	956	902	868	940
	# regions	178	178	178	173	164	176	178	178	178	173	164	176
Explanatory variable impact	nitrogen appl.	+	+	+	+	–	+	NA	NA	NA	NA	NA	NA
	field_size			+		+		+				+	–
	sgm		–		+								
	holdings_uaar		+	–							+		
	croparea_uaar				+	+	–	+			+	+	
	fert_uaar	+	+						+				+
	fnv_awu	+				+	–				+	+	
	acc50*	−|+				(−)|+					+|-		
	rugg	–				–	–						
	soil_pH	–				–				–			
	soc_topsoil_tc*		+|(−)				+|(−)	+|-	+|-			+|(+)	+|-
	swap	+		+	–	+		+	+	+			
	gdd*	−|-		−|-	−|(+)	−|-	−|(+)	(−)|-			(+)|+		−|+
	prcp_sum_year*	(+)|-		+|(−)			+|(+)		−|(−)				
	popdens*			+|(−)		+|-							