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ABSTRACT

The intensification, extensification and abandonment of agricultural land will each play a major role in the future development of European landscapes. However, their impacts on various dimensions of sustainability vary spatially. This creates challenges but also opportunities for landscape managers and policymakers to optimize biodiversity and ecosystem services. In this study, we conduct a spatial assessment of the impacts of these three major agricultural development trajectories on ten ecosystem service and biodiversity indicators across the European Union (EU) and the UK. Using a spatial resolution of 1 km2, we exposed high spatial variation in impacts and strong differences in the spatial patterns depending on the indicator. Aggregating all positive and negative impacts of a trajectory, hot- and cold spots of total positive and negative impacts could be distinguished. An assessment of trade-offs and synergies between impacts of each trajectory was used to map areas dominated by beneficial impacts, detrimental impacts, or high trade-offs between impacts. The results indicate very diverse spatial trade-off and synergy patterns, with generally high sub-regional variation, emphasizing (i) the need for reflecting trade-offs and context-specificity in landscape planning and management and (ii) the potential advantages of spatial targeting of agricultural development and conservation strategies. Biodiversity and ecosystem service impact mapping exercises can, thus, be a major tool to effectively navigate trade-offs and synergies and explore effective sustainable landscape solutions.

1. Introduction

Agricultural landscapes have a long history of anthropogenic use and cover almost half of the European Union (EU) land area in 2016 (Eurostat, 2019). The globalization and urbanization of the past 60 years have induced a diversity of changes in the European agricultural landscape, with dramatic impacts on the structure and composition of these landscapes (Antrop, 2005; Jepsen et al., 2015; Levers et al., 2018).

Predominantly in the most productive areas, agricultural intensification has transformed structurally complex and dynamic landscapes into hyper-productive but ecologically simplified landscapes through mechanization, scale enlargement and increased application of chemical pesticides and fertilizers (Jongman, 2002; Matson et al., 1997; Stoate et al., 2001; Tscharntke et al., 2005). As a trade-off, these landscapes lost multifunctionality, deteriorating regulating, supporting and cultural ecosystem services (ES) that support local well-being (Beckmann et al., 2019; Bouwman et al., 2009; Maes et al., 2011; Power, 2010). In the long term, the high productivity of these intensified systems might be undermined by land degradation, pollinator losses, and increasing natural hazards (Bommarco et al., 2013). Intensified landscapes also do not provide habitat to species that thrived in traditional agricultural landscapes and are a crucial component of European biodiversity and provider of ES (Billeter et al., 2008; Bucharova et al., 2020; Feniuk et al., 2019; Henle et al., 2008; Tscharntke et al., 2005). Furthermore, industrial agriculture is associated with externalities such as greenhouse gas emissions, eutrophication, and acidification of adjacent ecosystems (Kremen and Miles, 2012; Roe et al., 2019). Lastly, they serve as barriers between fragmented protected areas in a much-needed European green infrastructure network (Kremen and Miles, 2012; Maes et al., 2015).

On the other hand, in rural areas with low competitiveness or less favorable socioeconomic conditions, a trend of land abandonment is observed (Benayas et al., 2007; Lambin and Meyfroidt, 2011; Munroe et al., 2013). The impacts of land abandonment on ES and biodiversity are highly context dependent. In some cases, abandonment puts at risk agrobiodiversity and cultural heritage or causes increased wildfire risks or human-wildlife conflicts. In other places, agricultural abandonment

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may offer great potential to mitigate climate change by carbon sequestration in biomass and soils, and contribute to strengthening ecological networks and rewilding parts of Europe (Benayas et al., 2007; Munroe et al., 2013; Navarro and Pereira, 2012; van der Zanden et al., 2017).

The continuation of this intensification-abandonment polarization of European landscapes will lead to a loss of traditional agricultural landscapes. Maintenance of extensively farmed landscapes, as well as a decrease of intensity in agricultural areas with large environmental externalities, is promoted to protect cultural heritage and decrease negative impacts of agriculture on biodiversity and ES. Yet, also the preservation of, or conversion to, less intensive and more traditional forms of agriculture have trade-offs. Especially when combined with growing food demands, the potential yield loss caused by conversion to low intensity or organic agriculture – a 'land sharing' strategy) - (Barbieri et al., 2021; Seufert et al., 2012; Tscharntke et al., 2021) can indirectly cause agricultural expansion into more pristine habitats to maintain food production, within Europe or elsewhere. Thus, it can possibly have a net negative effect on biodiversity and ES (Kniss et al., 2016; Lambin and Meyfroidt, 2011). This is the main argument used to promote a 'land sparing' strategy, which advocates a continuation of the spatial segregation of nature conservation and high-yielding agriculture to secure more space for nature in the future (Green et al., 2005). This sharing-sparing framework provides ground for a meaningful comparison between alternative sustainable development options on a large scale (Balmford, 2021). However, since these agricultural land system changes generate such complex sustainability challenges and involve many trade-offs, they cannot be solved with the reductionist thinking reflected in the classic sparing vs sharing debate (Butsic and Kuemmerle, 2015; Ekroos et al., 2016; Grass et al., 2020; Merckx and Pereira, 2015).

In a more practical sense, the apparent dichotomy between these strategies is fading, as both strategies are viewed as two extremes of a spectrum of perceived desirability of integrating or segregating nature and agriculture at any given scale. Therefore, the focus for the European context has shifted towards more nuanced and targeted strategies that embrace both sparing and sharing strategies to meet various objectives in terms of biodiversity and ecosystem services (Feniuk et al., 2019; Finch et al., 2021; Grass et al., 2020).

As the impact of management system changes is likely to be strongly dependent on the local context, spatial targeting of interventions and policies to areas where the benefits are largest and costs are minimal could be a key lever to achieve optimized sustainability solutions (de Groot et al., 2010; Feniuk et al., 2019). Hence, understanding the trade-offs and synergies and managing drivers of landscape changes accordingly will be a major challenge for European policymakers and land managers.

Research to support such a more spatially targeted landscape management approach varies strongly in the spatial and temporal characteristics of analysis, affecting the support that can be given to policy and management (Mastrangelo et al., 2014; Spake et al., 2017; Tomscha and Gergel, 2016). At the EU scale, several studies have used quantification of ES and their co-occurrence to assess multifunctionality, synergies, trade-offs or identify hotspots (Maes et al., 2012, 2015; Mouchet et al., 2017a, 2017b; Verhagen et al., 2017). However, when such analysis is done at the aggregate spatial scale of administrative units (NUTS), trade-offs tend to reflect competition for space and are highly determined by the land cover distribution within the administrative unit. Consequentially, the interpretation of correlative approaches can be problematic, particularly when administrative units are heterogeneous and of varying size (Spake et al., 2017). Other studies have taken a more dynamic approach by conducting scenario-based impact analyses (Mouchet et al., 2017a, 2017b; Stürck and Verburg, 2017; van der Zanden et al., 2017; Verhagen et al., 2018). Such studies compare the impacts of a distinct set of scenarios of land-use change on ES supply, improving our understanding of the impacts of different political pathways and their uncertainties (Peterson et al., 2003). However, these studies only consider land-use changes depicted in the scenarios and do not provide insight into the potential impacts of land-use change in other locations. This paper aims at taking a different approach by mapping expected changes upon alternative trajectories for the entire agricultural area of the EU at high spatial resolution.

The objective of this paper is to, within the EU, assess the spatial variation in the trade-offs and synergies between potential ecosystem service and biodiversity impacts in response to three alternative agricultural land-use change trajectories: intensification, extensification and land abandonment. These trajectories represent the main processes of change in agricultural landscapes throughout the EU (Levers et al., 2018; Schulp et al., 2019; Stürck et al., 2018). Although they can vary widely in their implementation in terms of management practices, they relate directly to policy incentives and decision making at the farm level (van Vliet et al., 2015).

2. Materials and methods

2.1. Overview of methods

We started from the key premise that each km^2 of current agricultural land in the EU can potentially develop in the direction of either agricultural intensification, extensification or land abandonment. We assumed each trajectory has a characteristic ES supply and biodiversity impact profile, with pre-defined positive interactions (synergies) and negative interactions (trade-offs) between a set of selected ES and biodiversity impacts (hereafter both are referred to as ES impacts) (Fig. 1). Note that synergies in our study refer to impacts that have the same direction, it can also mean an interaction between two negative impacts. Although the direction of impacts (positive or negative) and interactions between them are assumed to always be the same for a particular agricultural change trajectory (Fig. 1), the size of each ES impact, as well as the strength of interactions, is expected to vary spatially (van der Zanden et al., 2017; Xiangzheng et al., 2016), affecting the desirability of the trajectory. This spatial variation in the strength of impacts and interactions will be the focus of this paper. Both carbon sequestration and rewilding potential are only calculated for the abandonment trajectories as the impact is either so locally variable (Chang et al., 2016, 2015; Ciais et al., 2010) or relatively small (Chang et al., 2015; Ciais et al., 2011) that it cannot be represented by a model. More detailed elaboration on this is given in Supplementary material C.

Fig. 2 provides an overview of the different steps used to progressively analyze spatial patterns of the aggregated ES impacts for each trajectory:

(i) We modeled a trajectory's potential impacts on a range of ecosystem service and biodiversity indicators.
(ii) We calculated an indicator of aggregated potential positive and negative ES impacts, identifying hot- and cold spots of each.
(iii) We compared total positive ES impact(s) with total negative ES impact(s) to identify areas with different trade-off patterns, indicating areas where a trajectory is potentially beneficial or detrimental, or where it potentially has strong trade-offs or low overall impact on ES.
(iv) We compared the outcomes between agricultural change trajectories
(v) To deep-dive into the results, we explored the coincidence of spatial patterns for each possible pair of potential ES impacts and mapped hotspots of their interactions.

2.2. Modeling of potential ES- and biodiversity impacts

For all agricultural grid cells, we modeled at a high spatial resolution (1 km^2) the potential impacts of each trajectory on ten different ecosystem services and biodiversity indicators (Table 1) for the entire EU, including the UK (hereafter: the EU). The ES represent provisioning ($n = 1$), regulating ($n = 4$) and cultural ($n = 1$) ecosystem services,

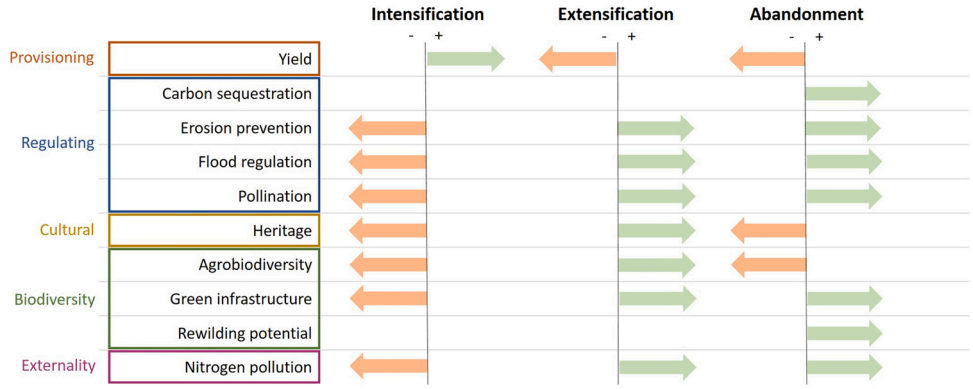

Fig. 1. Ecosystem service and biodiversity impact profiles of the agricultural change trajectories (green = positive, red = negative). Synergies exist between impacts of the same color. Trade-offs exist between impacts of contrasting colors. The size of each impact depends on the location.

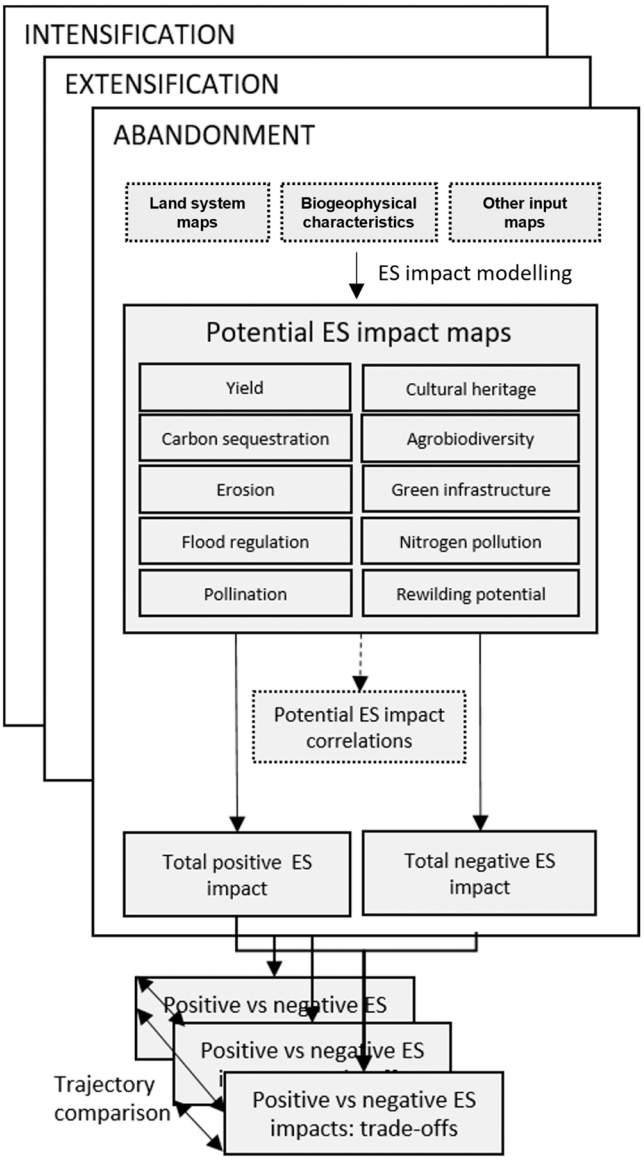

Fig. 2. Overview of methodology.

complementary biodiversity metrics (n = 3) and one environmental externality (n = 1). This selection is covering complementary key aspects relevant to landscape planning for sustainability aligned to EU policies. Important in the selection was the possibility to model the indicator at the scale of the study. Looking at the biodiversity metrics, different aspects of biodiversity conservation are reflected. At the species level, both species of cultural landscapes as well as those of more pristine landscapes are covered by the agrobiodiversity and rewilding potential indicators respectively. Ecosystem- and genetic diversity components are covered by the green infrastructure and rewilding potential indicators.

Five out of ten impacts were calculated using existing models documented in the literature that fit the EU context and scale of analysis. Models were adapted to fit the land system classification and incorporate newly available input data. The other five impacts were calculated using newly developed models (attainable yield, green infrastructure, erosion, nitrogen pollution, rewilding potential). In addition to the information in Table 1, documentation of each ES impact indicator model is included in Supplementary material C.

Each indicator of ES impact was calculated based on various input maps, such as land use type, topology, and species distributions. Depending on the model, either values of the grid cell itself, or of the grid cell and surrounding grid cells were determined as input to calculate the impacts.

The land system map that was used for all models was a 1 km^2 resolution EU land system classification (primarily based on the CORINE land cover map), developed explicitly to be meaningful for biodiversity modeling and assessments, with 14 different agricultural system classes that differentiate between multi-indicator intensity classes and mosaic classes (Dou et al., 2021).

The modeled ES impacts reflect the difference between the supply provided by the current agricultural land system and the supply of the intensified/extensified/abandoned state, assuming all other factors, including the state of surrounding grid cells, remain constant (Table 2). For intensification and extensification, we assumed that the overall land cover (grassland, arable cropland, permanent cropland) would remain constant, and the intensity class was raised or lowered one level. For agricultural abandonment, we assumed a conversion from the current state to a natural state (forest or shrub). Grid cells that were already attributed the maximal or minimal agricultural intensity class were excluded from the intensification and extensification impact calculation respectively.

2.3. Synergy and trade-off analysis

To compare ES impacts across indicators with different units, we standardized each impact map to a scale of 1–100 by reclassification into percentiles, 1 being the smallest impact, and 100 the largest. Then, we

Table 1
ES indicators used in the study; detailed documentation is found in Supplementary material C.

ES Type	Indicator	Indicator description [units]	Model documentation
Provisioning	Yield	Change in cropland or pasture agroclimaticcaly attainable yield [index]	Approach specific to this study
Regulating	Carbon sequestration	Potential carbon capture in biomass upon abandonment within the next 30 years [Mg C / km^2 / 30 yr]	Cook-patton et al. (2020)
	Erosion prevention	Mean annual soil loss rate [ton/ha/year]	Based on Panagos et al. (2015)
	Flood regulation	Flood regulation supply index [index]	Based on Stürck et al. (2015, 2014)
	Pollination	Cropland pollination by wild bees [index]	Based on Verhagen et al. (2018)
Cultural	Heritage	Cultural value/meaning index [index]	Based on Tieskens et al. (2017)
Biodiversity	Agrobiodiversity	Relative species richness of farmland vertebrates and plants [fraction of max possible species present]	Based on Overmars et al. (2014)
	Green infrastructure	Contribution to the expansion and defragmentation of a European green infrastructure network [index]	Approach specific to this study
	Rewilding potential	Ecological potential of currently agricultural land to successfully re-wild [index]	Based on ecological integrity by Fernández, unpublished
Externality	External nitrogen pollution	Nitrogen surplus damage on adjacent nature [index]	Approach specific to this study

Table 2
Agricultural land use classes that were used in the study and the intensified, extensified, and abandoned states for which ES impacts were calculated. '-' indicates that the respective state was not included in the study because the grid cell is already at maximal/minimal management intensity. For detailed descriptions of the land system classification, see Dou et al. (2021).

Initial agricultural land system	Initial management intensity	Intensified management intensity	Extensified management intensity	Abandoned land system
Arable cropland	Low	Medium	-	Forest/shrub
	Medium	High	Low	
	High	-	Medium	
Permanent cropland	Low	High	-	Forest/shrub
	High	-	Low	
Grassland	Low	Medium	-	Forest/shrub
	Medium	High	Low	
	High	-	Medium	
Cropland and grassland mosaic	Low	Medium	-	Forest/shrub
	Medium	High	Low	
	High	-	Medium	
Forest/shrub and cropland mosaic	Low	Medium	-	Forest/shrub
Forest/shrub and grassland mosaic	Low	Medium	-	Forest/shrub
Forest/shrub, cropland, and grassland mosaic	Low	Medium	-	Forest/shrub

made a subset of each standardized map by keeping only the 50 highest percentiles, which we somewhat arbitrarily defined as 'substantial'. To identify areas with strong coincidence amongst either all substantial positive or negative impacts, we then aggregated all standardized impact maps of the same direction into a single total positive- and negative ES impact indicator. This was done for each agricultural change trajectory.

To identify different trade-off patterns, we compared the total positive with the total negative ES impact maps. For this, we first classified both the total positive and negative ES impact indicators into three classes (low – medium – high) based on an equal distribution of observations across the classes. Based on the combination of positive and negative impacts, each pixel was then classified in one of nine potential combinations of positive and negative impacts, following the scheme in Fig. 3. By mapping these combinations, insight is obtained into the spatial distribution of the overall size of the impacts as well as the different trade-off patterns. Where positive impacts are small and negative impacts are large, we classify these are 'detrimental'. Where negative impacts are small and positive effects are large, we classify the impacts as 'beneficial'. For example, intensification is considered more beneficial where it results in medium to high yield gain and low negative ES impacts. Vice versa, it is considered detrimental. The higher both positive and negative ES are, the stronger the trade-off. As a final step, we mapped the spatial overlap of the beneficial and detrimental areas, defined as in Fig. 3, for all three trajectories across the EU.

2.4. Pairwise ES trade-offs and synergies

The analysis of synergies and trade-offs by aggregating across multiple ES impacts does have drawbacks. Despite only working with 'substantial' impacts, i.e., above median impacts, some substitution between different ES impacts might occur. The analysis also does not provide insight in the underlying interactions between individual ES impacts. Some patterns of ES impacts are expected to be more correlated than others, as they are governed by similar processes. To identify whether hot- and coldspots of different impacts coincide or not, we also analyzed pairwise correlations between the spatial patterns of potential impacts of different ES. We did so by calculating pairwise correlations between all standardized impacts maps, resulting in a correlation coefficient matrix for each trajectory. We also mapped the locations where each pairwise interactions were most pronounced by mapping those locations where standardized impacts of the pair of indicators were above median, using the sum of both standardized impacts as a measure of the strength of the interaction, be it a trade-off or synergy.

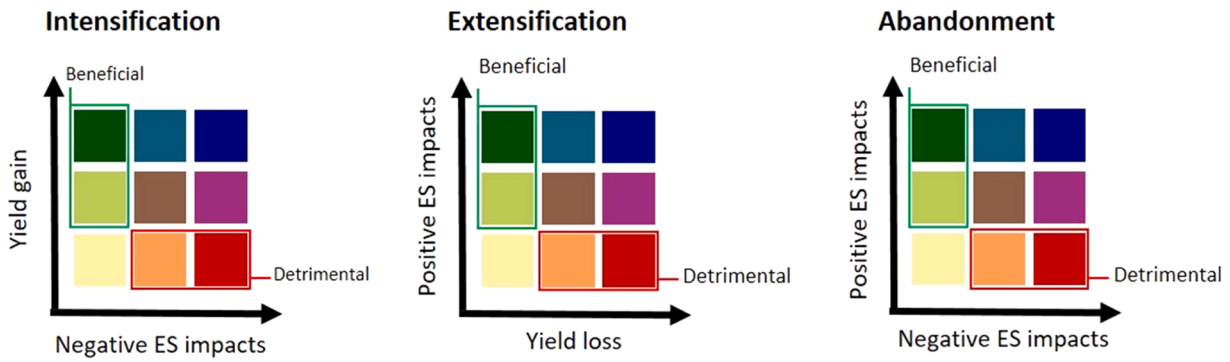

Fig. 3. Classification of the different combinations of positive and negative impact(s) classes for each trajectory. Combinations that are considered beneficial and detrimental are indicated.

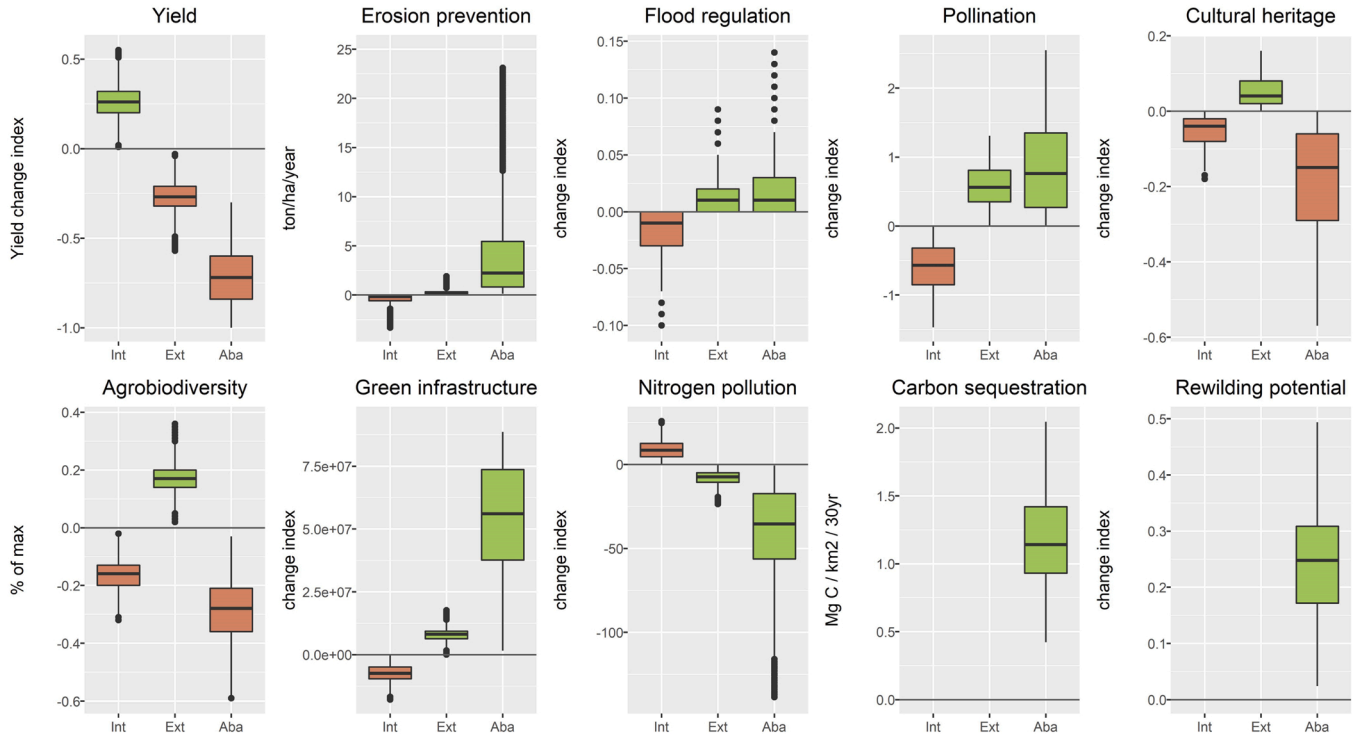

Fig. 4. ES impact size distribution boxplots per ES and per trajectory.

3. Results

3.1. ES- and biodiversity impact modeling

Fig. 4 shows the effect size distribution of potential ES impacts, whereas maps for each of the ES in Supplementary material A show the normalized spatial variation of ES impacts for each trajectory.

ES impacts of intensification, extensification and abandonment show distinct spatial patterns. ES impacts of abandonment are consistently larger compared to those of management intensity changes since it is a more drastic change with stronger impacts on ecosystem structure and functioning. Still, the overlap of the distributions shows that the impacts of extensification in one site might be larger than those of abandonment at another site. The difference between abandonment and intensity change impacts was more pronounced for some ES impacts (GI, erosion prevention) than for others (flood regulation, pollination) (Fig. 4).

For some ES (yield, flood regulation, pollination, green infrastructure) there was high agreement in the areas that are most sensitive to the different trajectories.,. For other ES (erosion, agrobiodiversity, nitrogen pollution), low and high impact locations were trajectory-dependent, being either the result of the initial state of agricultural land use at the location or differences in the mechanisms with which intensity changes and land abandonment affect ES.

Carbon sequestration and, to a lesser extent, yield gain/loss show gradual spatial patterns of ES impacts. Both are highly determined by climatic conditions. Hotspots of erosion prevention and flood regulation impacts, both showing exponentially distributed impact sizes (Fig. 4), are concentrated in a few locations with respectively steep slopes and in crucial watershed zones, whereas in many other regions, relatively low impacts are observed. Hotspots of impacts on pollination are found in vast agricultural landscapes where highly pollination-dependent crops are cultivated. Cultural heritage impact hotspots show a more clustered pattern, with varying densities of small hotspots. The impacts of changes in agricultural intensity on heritage values depend on the initial landscape structure and management intensity of the location, whereas abandonment always causes a total loss of cultural heritage in the model used. Similar but more gradual clustered patterns were found for agrobiodiversity, and the locations of clusters strongly differs between

trajectories, reflecting the consideration of differential sensitivities of local species in the model. Green infrastructure impacts are maximal in highly fragmented natural landscapes and decrease quickly towards the core of agricultural landscapes. Spatial variations in nitrogen pollution impacts differ between trajectories, due to the model dependency on country-specific nitrogen loss values associated with the different intensity levels. Still, some regions of high sensitivity are highlighted in all trajectories. The potential for rewilding upon abandonment is high in regions with high proportions of non-disturbed nature, while the potential is relatively low in highly urbanized and agricultural areas.

3.2. Synergy and trade-off analysis

Fig. 5 displays maps of the total aggregated negative (left) and positive (right) ES impact indicators for each trajectory, yield impacts being the only positive and negative ES impact for respectively the intensification and extensification trajectory. Country and land system class averages for the impact indicators can be found in Supplementary material B.

Intensification: The impacts of intensification on yields are highly determined by spatial variation in climatic conditions, with variations caused by irrigation. Although some countries generally show high (Italy) or low (Northern European countries) negative impacts on the other ES, most countries show significant regional and sub-regional differences. Large hotspots of negative ES impacts are found in Northern Italy, central Romania, Southern Poland, Eastern and Southern France. On average, areas currently dominated by low-intensity grasslands show the highest total negative ES impact upon intensification (Supplementary material Table B1).

Extensification: The highest impacts upon extensification are found in medium and high-intensity grasslands and permanent croplands (Supplementary material Table B2). Yield impact patterns show high agreement with those resulting from intensification, and areas with overall high positive ES impacts of extensification show similar patterns to those of high negative ES impacts of intensification (Southern Poland, Slovakia, Southern Germany, Eastern France, Southern Spain). However, in the Czech Republic, central France, Southern Spain and Western Ireland, positive ES impacts upon extensification are high, whereas negative ES impacts of intensification are relatively small. In Italy, Bulgaria and the France-Spain border region, the opposite pattern was found. Whereas large areas with low negative ES impacts of intensification occur in Northern Europe, areas with low positive impacts of extensification are found in Northern Spain, Northern France, Central Poland, Northern Germany, Hungary and Bulgaria. Some of these differences are caused by differences in data coverage of both trajectory maps, due to no possibility for further intensification or extensification in some regions (e.g., France, Ireland, France-Spain border, Bulgaria, Southern Spain where agriculture is already in the most intensive or extensive class).

Abandonment: On average, the most positive impacts are found in areas currently dominated by high-intensity croplands, while the most negative impacts occur in those dominated by permanent croplands and low-intensity grasslands (Supplementary material Table B3). Countries show mixed impacts of agricultural abandonment, except for northern Europe and Ireland, where hotspots of negative impact are rare. The largest continuous hotspots of positive impacts are found in Northern and Southern France, Northern Bulgaria, Western Hungary, the Czech Republic, central Romania, and the Poland-Slovakian border region. Large coldspots of positive ES impact occur in South-East Italy, central Poland, central Spain, South-central France, Latvia and Lithuania. Large areas of high negative impact were found in Southern Spain, Southern Greece, Southern France and Southern Poland. Relatively small negative ES impacts are found in vast continuous areas in multiple countries (France, Spain, the UK, Bulgaria, Hungary, Estonia, Norway and Finland) and throughout Ireland.

Maps in Fig. 6 show spatial patterns of all nine possible combinations of positive and negative ES impacts Each combination reflects a different impact pattern, expressed in terms of both the overall size of impact as well as the level of trade-offs. The higher both positive and negative ES impacts are, the stronger the potential trade-offs. When positive ES impacts are high, and negative ES impacts are low, the respective trajectory was considered more beneficial. Vice versa, the trajectory was considered detrimental. Table 3, as well as the pie charts in Fig. 6 display the proportions in which each of the nine combinations occur for each trajectory.

Intensification: Areas where intensification would have mostly beneficial impacts, identified by potentially high yield gain and low aggregated negative ES impacts, occur more often towards Northern Europe. Apart from larger regions in Denmark, Sweden, Poland, Lithuania and Ireland, small areas occur scattered across most Western European countries. Areas where intensification could be considered most detrimental, identified by potentially high negative ES impacts and low yield gains, occur almost exclusively in Southern Europe. Substantial parts of Italy, Spain and Austria are classified as such, and small areas are scattered throughout central Europe. High trade-off areas are dominant in central Europe, Romania and Poland, but are also found, in smaller areas, in nearly all other countries.

Extensification: Areas where extensification is considered detrimental due to low positive ES impacts and high yield loss are found predominantly in central and northern Europe. Such locations cover a much smaller area (5.8%) than other combinations (Table 3). To a lesser extent this is also observed for the areas with the most beneficial impacts of extensification (7.6%), that occur more frequently in Southern Europe. Much more present are low impact zones (15.6%), dominant in Spain, Italy, France, Hungary and Bulgaria and strong trade-off areas (15.3%), dominant in large parts of Western and Central Europe.

Abandonment: Patterns of impacts upon abandonment are more complex than those of intensification and extensification, as this trajectory can have both multiple positive and negative ES impacts with diverging spatial distributions. Except for Ireland, every country harbors a great spatial variation in the different total positive and negative ES impact combinations. Areas where abandonment would be most detrimental, with potentially low positive ES impacts and high negative ES impacts, are scattered across the EU. Larger areas occur in Italy, France, Spain, Poland, Greece and the Netherlands. This spatial pattern differs from that of areas where abandonment is more beneficial due to positive and low negative ES impacts. While these more beneficial impacts of abandonment are missing in many regions, they occur concentrated in larger areas in Spain, the UK, France, Bulgaria, Hungary and Estonia. Strong trade-off areas and areas with low overall impact occur in nearly all countries.

Fig. 7 displays the areas considered as either beneficial or detrimental for one or more of the three trajectories, following the classification in Fig. 3. Areas that are beneficial and detrimental for the same trajectory are spatially separated at the continental scale but co-occur on fine spatial scales. For intensification, this is more apparent than for extensification. For abandonment, we find fine-scale adjacency of locations where abandonment would be detrimental and beneficial in Germany and Eastern European countries.

In most places, only one trajectory is classified as either beneficial or detrimental. However, areas beneficial for both abandonment and extensification occur in large and distinct regions such as large parts of Hungary and in several areas of France and regions in Southern Spain, Greece and Slovakia. Presumably, these are places with high potential for improvement in many regulating ES, green infrastructure and nitrogen pollution, which both trajectories affect positively. Areas where both intensification and abandonment are detrimental occur most often in Spain, Latvia, Greece, Hungary, Italy, Lithuania and Portugal, leaving extensification as the preferred development option in terms of ES impacts. In central Poland, Denmark, as well as large parts of Latvia and Lithuania, extensification and abandonment are considered detrimental, while intensification is considered relatively beneficial.

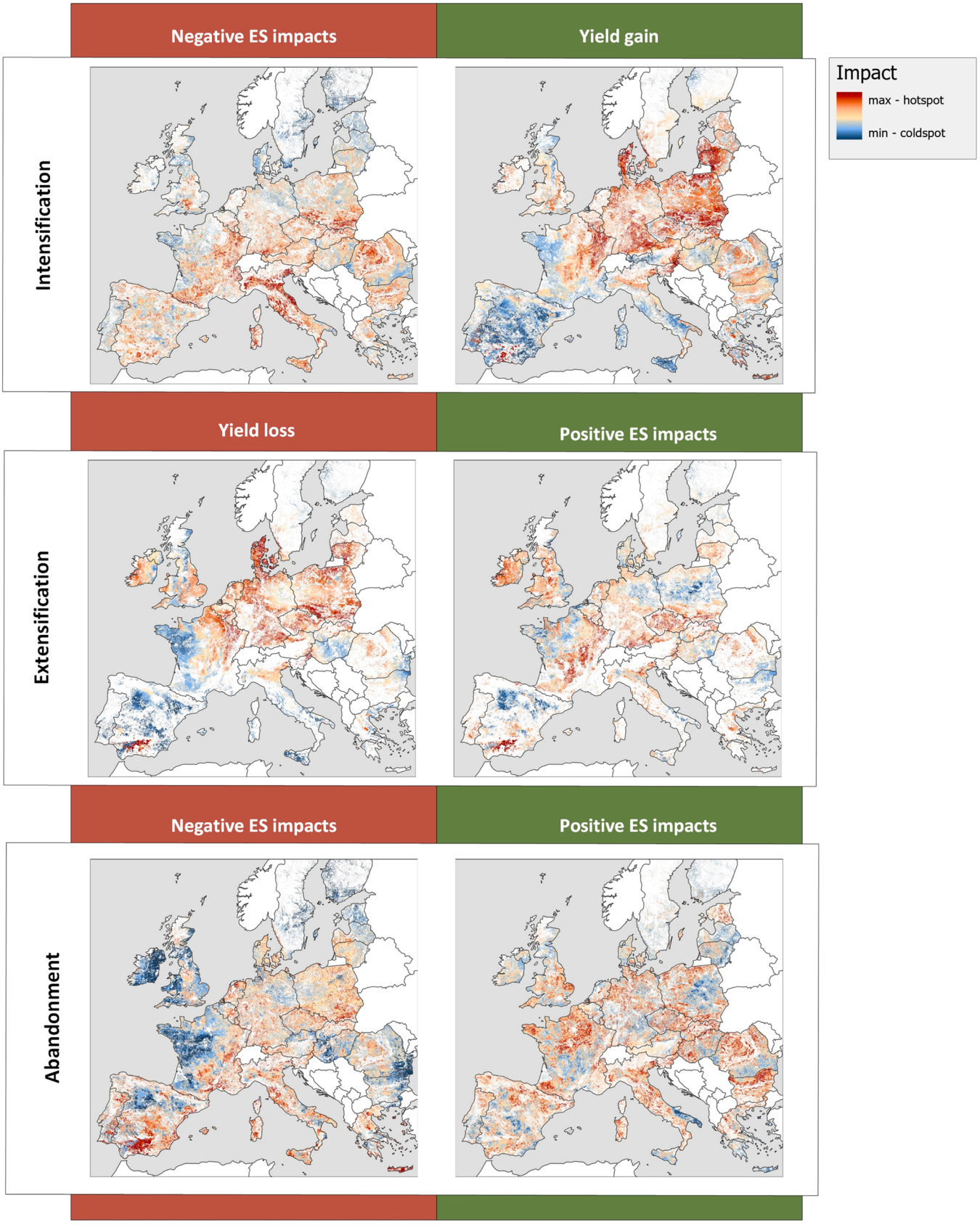

Fig. 5. Total positive and negative ES impacts of different agricultural change trajectories. Maps indicate the sum of above-median standardized positive and negative impacts respectively. In case of the abandonment trajectory, the negative yield impacts (loss of agricultural production) are added to other negative impacts. For intensification and extensification, yield impacts are always opposite to those on other ES.

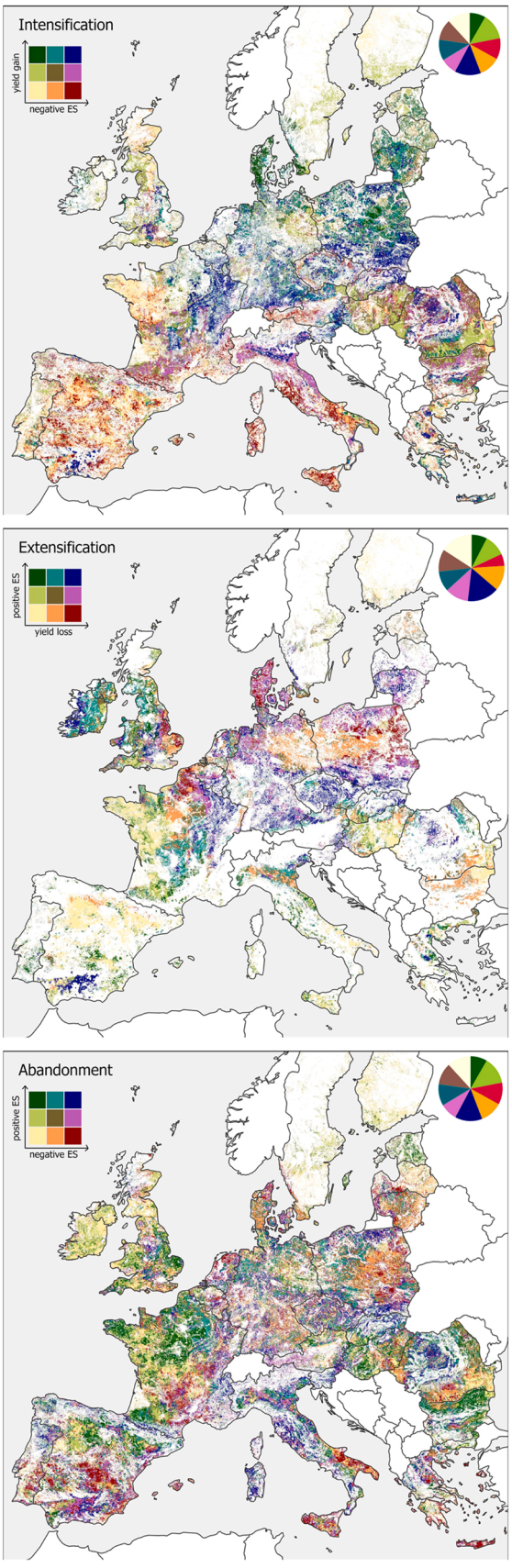

Fig. 6. Positive vs negative ES impact(s) for each trajectory. Coverage differs amongst trajectories because not all grid cells can be intensified/extensified.

Overall, there are strong differences between countries in the proportion of agricultural land on which trajectories are considered beneficial and detrimental (Supplementary material Table B8–9), as well as their spatial patterns of co-occurrence (landscape, regional, national) within. Hungary stands out as having exceptional sub-regional spatial variation throughout the country, with a mixed occurrence of locations beneficial for one or two trajectories. In Western and Southern France, a similar situation is found. In South-west UK, as well as Northern Italy, areas with beneficial and detrimental impacts of abandonment and extensification occur adjacently. In North-West France, there is a mixed occurrence of agricultural lands that are expected to have beneficial and detrimental impacts for all three trajectories. In Northern Portugal, locations where intensification and abandonment are considered detrimental are mixed with locations beneficial for all three trajectories. All trajectories would be beneficial in considerable parts of the UK and Italy, though they are more spatially separated. The Baltic states are relatively homogeneously classified into dominant classes.

3.3. *Pairwise and multifunctional correlations*

To provide context and better insight into the underlying causes of the identified positive and negative impacts and trade-off patterns, a pairwise analysis of correlations between the spatial patterns of standardized ES impacts was done (Fig. 8). The results indicate that different pairs of ES indicators are either showing overlapping hotspots, or clearly spatially separated hotspots. Additionally, maps showing the locations where both ES impacts are maximal for ES pairs, are provided in Supplementary material A. Due to very large (>15 million) sample size, all correlations were highly significant. The maximum and minimum correlation coefficients between spatial patterns of ES impacts range from 0.43 (extensification impacts on agrobiodiversity & green infrastructure) to − 0.4 (abandonment impacts on carbon sequestration & rewilding potential), indicating that hotspots range from strong overlap to clear spatial separation. In the spatial Also for intensification coinciding patterns of impacts on agrobiodiversity and green infrastructure impacts are found, indicating that prevention of intensification and stimulation of extensification will in many areas lead to relatively high positive effects on both agrobiodiversity and green infrastructure. For abandonment, two clusters of positively associated spatial patterns are found. The first consists of pollination, flood, green infrastructure, and nitrogen loss, which are all positively correlated to spatial patterns of yield impacts. The other consists of agrobiodiversity, erosion, cultural heritage and rewilding potential, which are negatively correlated to the spatial pattern of yield impacts. Further, carbon sequestration impacts have a single positive correlation with the spatial pattern of impacts on yield while negatively associated with patterns of multiple other impacts, suggesting that regions where abandonment is relatively beneficial for carbon sequestration tend to also have strong yield trade-offs (likely as part of relatively high productivity), and limited impacts on other ES.

4. Discussion

4.1. *Reflections on the main results and policy recommendations*

The results of this study provide evidence of the huge spatial diversity in the patterns of impact on ecosystem services and biodiversity upon different trajectories of agricultural change, displaying the EU as a patchwork of strongly diverging decision-making contexts for landscape change planning and management. The results expose both large scale patterns as well as high supra- and sub-regional variation in the potential ES and biodiversity impacts of each trajectory and their interactions. The multi-scale complexity of landscape-level impacts shows the need for integrated and multi-scale spatial planning, with at its core the valuation of agricultural landscapes for a variety of public goods they deliver, as advocated by many scientists and practitioners (Pe'er et al.,

Table 3
Proportion of grid cells classified as each of the 9 combinations of positive and negative impact classes for each trajectory.

Positive impact class	high	med	low	high	med	low	high	med	low
Negative impact class	low	low	low	med	med	med	high	high	high
Intensification	0.086	0.138	0.116	0.112	0.110	0.110	0.132	0.082	0.115
Extensification	0.076	0.108	0.156	0.097	0.112	0.120	0.153	0.119	0.058
Abandonment	0.110	0.115	0.117	0.113	0.110	0.107	0.107	0.109	0.112

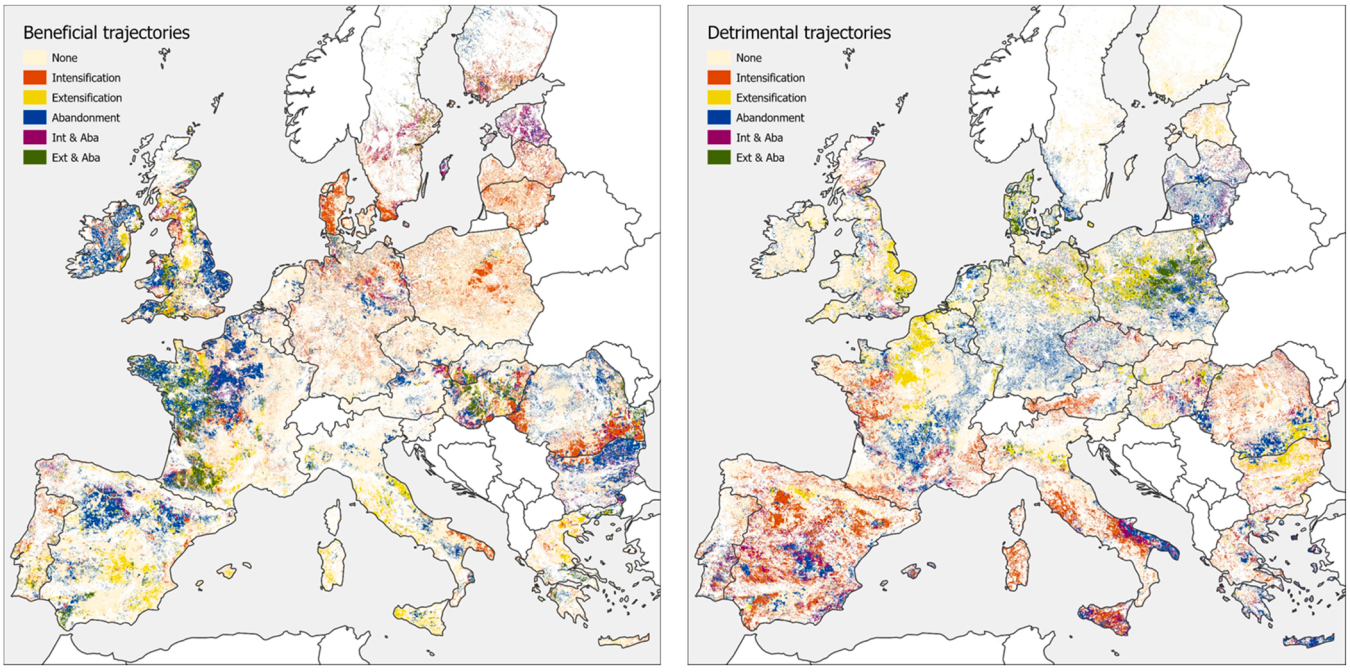

Fig. 7. Inter-trajectory comparison of beneficial and detrimental areas. Negligible numbers of grid cells were beneficial or detrimental for both intensification and extensification, or for all three trajectories. Hence, they were not included in the maps.

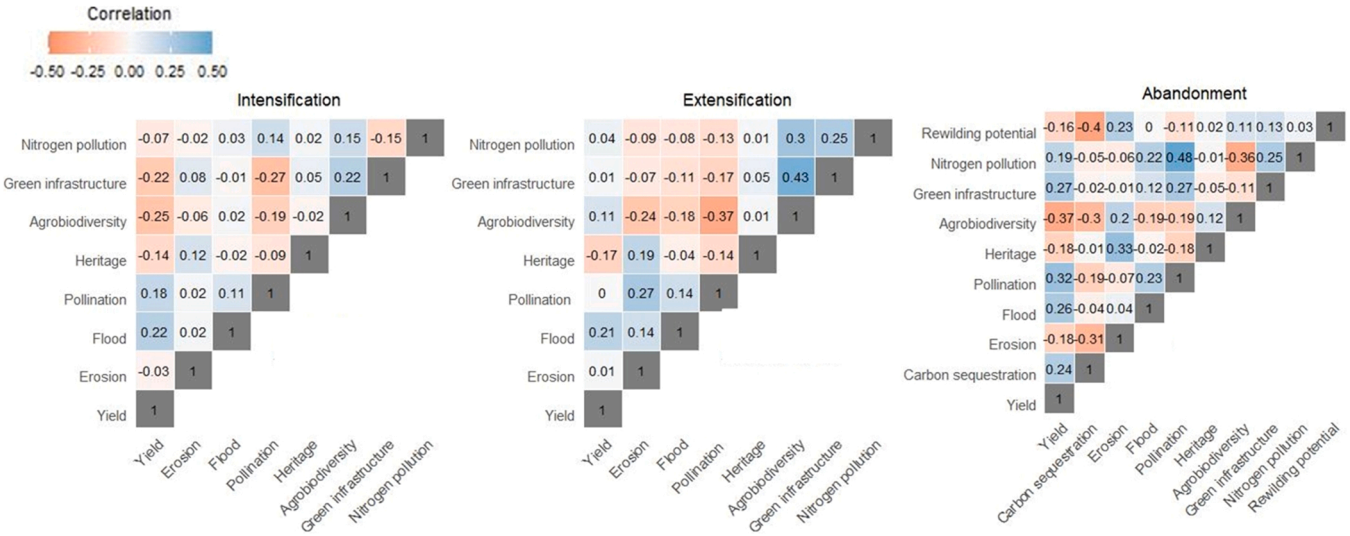

Fig. 8. Correlation coefficients, indicating the correlations of the spatial pattern of impacts between pairs of potential ES impacts for each trajectory.

2020).

Yet, this complexity is not fundamentally reflected in EU policies such as the Common Agricultural Policy (CAP) and the legal framework of the Bird's and Habitat's Directive and Natura 2000 network, being one of the most dominant drivers of agricultural and nature conservation developments and policies (Fuchs et al., 2013; Lefebvre et al., 2012; Simoncini et al., 2019). The integration of agronomic and nature conservation policies is very limited, as is their spatial explicitness and context-specificity, causing discrepancies between both, with inefficiency in meeting objectives on each front as a result. Moreover, areas differ strongly in the types of measures that are most effective, and there is a discrepancy between the most effective and the most adopted

measures. Hence, its effective use of public funds is much criticized (Batáry et al., 2015; Naidoo et al., 2006; Pe'er et al., 2020, 2017; Recanati et al., 2019; Scown et al., 2020; Wünscher et al., 2008). As the CAP is the biggest EU spending, and national environmental schemes (AES) budgets often surpass any other conservation budgets (Batáry et al., 2015; Heyl et al., 2020), redesigning EU policies to better accommodate the need for integration and multi-scale spatial planning can be a major leverage point in achieving more sustainable land-use (Heyl et al., 2020; Nicholas et al., 2021).

Although the resolution and specificity of results are not sufficient to be of direct use for regional or local practitioners, the high variation in the results of our analysis confirms the need for EU policies to allow and stimulate Member States to customize the actions according to the local context and improve the spatial targeting of funding based on estimated trade-offs. Although the need for increased flexibility and tailoring is addressed by the national strategic plan-approach of new CAP (European Comission, 2021), spatial targeting and a bigger role for strategic spatial planning to achieve this is not addressed. Without careful spatial planning, the increased flexibility may not address the spatial trade-offs reflected in our analysis. Furthermore, the focus of greening measures heavily lies on on-farm biodiversity without considering trade-offs with yield losses, leakage effects and agricultural expansion, possible offsetting on-farm benefits (Barreiro-Hurle et al., 2021; European Commission, 2019). By not addressing trade-offs and spatial targeting, inconsistency remains between the protected area-focused and farmland-focused goals of the new CAP and the EU biodiversity strategy for 2030 (The European Commission, 2020).

Our study complements existing 'static' European ES and biodiversity mapping studies (Crouzat et al., 2015; Maes et al., 2012; Mouchet et al., 2017) by focusing on the impacts of potential changes. As opposed to scenario-based approaches (Maes et al., 2015; Mouchet et al., 2017; Stürck and Verburg, 2017), this study not only shows the collective impacts of a specific scenario but rather exposes the potential impact of alternative trajectories on all EU farmlands. Compared to existing conservation prioritization studies (O'connor et al., 2021; Verhagen et al., 2018, 2017), our study does not solely focus on prioritizing high-quality areas but rather highlight regions of relatively high conservation potential, with synergies amongst positive impacts, high risk areas with strong coincidence of negative impacts, or areas with high trade-offs upon changes in agricultural management.

Reflecting on the sustainable management of agricultural intensification, yield gains are considered necessary to minimize the agricultural expansion of accommodating increased food demand at minimal natural costs, or imports from other parts of the world and associated environmental damage (Barbieri et al., 2021; Grass et al., 2020). Although this necessity can be diminished by food system changes such as more land-efficient dietary patterns and reduced food waste (Barbieri et al., 2021), yield will have to be maximized without compromising long-term resilience and the condition of 'spared' lands (referred to as sustainable intensification; Garnett et al., 2013; Scherer et al., 2018). Locations of high yield gain and low environmental costs were found scattered throughout all EU Member States, although occurring progressively more often towards Northern Europe. When comparing these results to scenario studies that identified areas with high intensification likelihood, there is a match between the most desirable areas detected in this study and areas of high likelihood of experiencing an intensification trajectory in the future (Levers et al., 2018; Stürck et al., 2018). Such outcome reflects the potential for sustainable intensification.

In contrast, we found large national and regional differences in the proportions of farmland where intensification would be detrimental. In the Southern half of the EU, large proportions of farmland showed relatively low yield gains and high negative ES impacts. Especially from a continental perspective, it is hard to justify large-scale agricultural intensification in these regions.

According to European green deal, a quarter of the agricultural land should be farmed organically by 2030 (EC, 2021). While organic farming is not the same as extensification, the results of our analysis can show where the potential for ES and biodiversity improvement are maximal, and the expected yield losses minimal. This pattern occurred most often in Southern Europe, the UK and Ireland. At the same time, in most Member States the least desirable combination of low positive ES impacts and high yield losses, is relatively rare. Where positive ES impacts of extensification are high, yield costs tend to also be so. In accordance with various studies about the effectiveness of agri-environmental schemes for biodiversity (Batáry et al., 2011), we found that productive, intensively farmed landscapes that are ecologically impoverished and simplified, particularly grasslands, potentially benefit most strongly from extensification, not only in terms of biodiversity but also for ES. However, this tendency of high yield costs resonates with the widespread criticism on the effectiveness of de-intensification subsidies and the call for more result-based subsidy systems (Batáry et al., 2015; Scown et al., 2020; Sidemo-Holm et al., 2018).

Land abandonment forms an important challenge for European policymaking because of the variety of different possible outcomes and people's perceptions (Benayas et al., 2007; Fayet et al., 2022; van der Zanden et al., 2017). In line with previous studies, our results expose the high complexity of the landscape with respect to abandonment impacts, showing exceptional variation in the combined ES and biodiversity impacts on small spatial scales. Comparing our results with land abandonment risk maps of Castillo et al. (2021), there is no clear overlap between the regions with a high likelihood of facing abandonment and the regions identified in our study as having desirable impacts upon abandonment. This may imply that, without more targeted spatial planning and policy, abandonment might lead to undesirable impacts. Although both extensification and abandonment can have a range of positive impacts on ecosystem functioning, in areas, such as parts of Greece, Spain and Portugal, our results indicate that extensification might be the better conservation option due to high agrobiodiversity and cultural heritage values as compared to the potential benefits of agricultural abandonment. Because abandonment impacts were found to be in general much larger than extensification impacts, abandonment may offer greater absolute improvement in areas where both trajectories are considered as beneficial, prominent in Hungary, Sweden and France, potentially offering additional benefits of rewilding and carbon sequestration.

Now, the CAP only addresses land abandonment directly by the allocation of 4% of the budget towards supporting farmers in Less Favored Areas (LFA) to halt succession, maintain low-intensity farming systems and support public services (Merckx and Pereira, 2015). These LFA subsidies, as well as many AES, are often directed to Natura2000 zones and areas where abandonment would be beneficial, according to our results. Especially in the light of the EU 2030 biodiversity strategy, which aims to protect 30% of EU land, of which 10% strictly protected (EC, 2020), the current LFA subsidies might act against these objectives. In these areas, EU funding would be spent more effectively on the encouragement of rewilding practices (Merckx and Pereira, 2015). Zooming in on two unique assets of the rewilding approach: rewilding and carbon sequestration, our results showed a spatial separation between the areas where potential positive impacts of abandonment on both were the highest.

4.2. Methodological considerations

The methods used and assumptions made in this study have consequences for the interpretation of the results and the conclusions that can be drawn from the study. Firstly, the choice of indicators is a major determinant of the study results. Although we have aimed to cover complementary indicators, different indicators would have led to different results. Although we consider carbon sequestration, we do not consider the carbon stock impacts of management intensity changes, while these might also be important, especially in peatland regions.

Similar arguments can be made for other additional indicators that could potentially be added to the approach. Other factors that might have influenced our results relate to the methods used. Firstly, potential ES impact values, total impact indicators, and detrimental and beneficial areas are always relative in comparison to the impacts of the same trajectory in the rest of the EU. While some impacts can be relatively small, these might be significant at a regional or national scale and affect important ES for local populations. Secondly, results reflect the potential impact of trajectories within each grid cell, assuming the surrounding landscape to remain the same. For some services like green infrastructure, pollination, agrobiodiversity, rewilding potential and nitrogen pollution, potential impacts depend on the state and dynamics of surrounding grid cells. The models that we used do not account for these impacts of change at scale, which can either lead to more beneficial or more negative outcomes. Future studies could focus on the impact of the scale of agricultural management changes or optimize land-use changes in the EU for a given set of objectives.

When identifying regions where certain trajectories would be most beneficial or detrimental, the analysis is based on the selected set of impacts. There is a wider range of impacts, including socio-economic impacts, not accounted for in this study. These should be accounted for in the actual targeting of policies. Lastly, in our methods, we extrapolate the impacts of current intensified agricultural systems. However, it is well possible that future forms of sustainable intensification achieve the same yields with lower levels of nitrogen pollution, erosion risk, flood risk etc. However, we chose to follow the precautionary principle, since not making that assumption would paint a more optimistic future that has not actually been realized.

5. Conclusion

The agricultural change trajectories of intensification, extensification and abandonment will each play a major role in the future development of European landscapes. While ach trajectory has characteristic positive and negative impacts on different sustainability indicators, we found strong spatial variations across the EU in the patterns of trade-offs and synergies between these indicators. The results of our analysis show that the same trajectory can have a dominance of beneficial or detrimental impacts, depending on location. For policy makers to navigate trade-offs and maximize positive synergies, a spatial perspective is essential, Hence, science-based spatial planning, is a key tool that can contribute to meeting European agronomic and conservation objectives. By comparing the impacts of contrasting management alternatives, these results contribute to informing choices on locations for either land sparing or land sharing and emphasize the need for nuance and risk of interpreting the debate on different agricultural development trajectories in a dichotomous sense.

CRediT authorship contribution statement

Leen Felix: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Roles/Writing – original draft, Writing – review & editing. **Peter Verburg**: Conceptualization, Investigation, Methodology, Project administration, Roles/Writing – original draft, Writing – review & editing, Funding acquisition, Supervision, Validation. **Thomas Houet**: Funding acquisition, Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.07.004.

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