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Agricultural intensity interacts with landscape arrangement in driving ecosystem services

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ABSTRACT

Agricultural intensification has enhanced productivity but also led to enormous ecosystem service and biodiversity losses. Strategic spatial landscape design could counteract this trend, but, the scientific understanding of how ecosystem services respond to agricultural practices on one hand and land use composition and configuration on the other is not complete. This study aims to methodically explore how the effect of landscape layout settings on ecosystem services depends on the intensity of agricultural practices in their surroundings. Using the Netherlands as a case study, we used spatial regression models to analyze how agricultural management intensity affects the relationship between spatial composition and configuration metrics and ecosystem service indicators. We found that the effect of large shares of agricultural land use on species richness, pollination and landscape appreciation was increasingly negative with amplified intensity of agricultural practices. With higher agricultural intensity in the surroundings, the positive effects of well-connected natural vegetation on species richness were impaired. In contrast, the negative effects of high-intensity agriculture on pollination service were be buffered well through high shares of natural grassland vegetation. Water-quality related indicators were less affected by variation in spatial metrics and agricultural intensity. The main interactions between agricultural intensity and the spatial metrics were robust at varying scales. Our analysis suggests that both low- and high-intensity agriculture can have a place in future sustainable agricultural systems, provided they are integrated in the appropriate spatial layout. Explicitly addressing farming practices in connection to local spatial settings can improve both landscape planning and ecosystem service modelling.

1. Introduction

Global agricultural production has grown considerably in the last decades, mainly due to yield gains that were accomplished through management practices, such as high use of artificial fertilizer and pest control chemicals, irrigation, mechanization, simplification of crop rotations and crop breeding efforts (Foley et al., 2011; Egli et al., 2018). During this process, landscapes have become more homogeneous, consist of less natural and semi-natural elements, and are increasingly dominated by large agricultural fields with monocultures (Persson et al., 2010; Cormont et al., 2015). These aspects of agricultural intensification have resulted a rise in food and feed production, but also in soil and water degradation and biodiversity loss due to habitat destruction on and off farmland (Allan et al., 2015; Qiu et al., 2021).

Among other countries, the Netherlands stand out as a country with high agricultural intensity in the sense of high inputs of agrochemicals to the fields, large-scale mechanical soil cultivation and a livestock density of more than four times than the European average. However, the high-input agriculture in the Netherlands has also led to significant biodiversity loss, as well as poor water quality and soil degradation (Erisman et al., 2016; Vermunt et al., 2022). Within Western Europe, the same trends can be observed due to similarities in farming management and landscape structure (Emmerson et al., 2016; van der Zanden et al., 2016) that are driven by the same 'productivist' market logics and supporting policies and finances (Scown et al., 2020; Vermunt et al., 2022). The Netherlands can therefore be considered an exemplary case study for future trends in other European countries, not only in terms of agricultural impacts, but also for the design of solutions that reconcile agricultural productivity with safeguarding ecosystem services and biodiversity.

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The Dutch policy goals contain a transition towards a more sustainable agricultural system, partly through targeted spatial planning (Tisma and Meijer, 2018), which has been recognized as a potential way to foster the provision of undersupplied ecosystem services in global studies as well (Foley et al., 2005; Duarte et al., 2020). Following this premise, researchers have investigated the influence on the provision of various ecosystem services of spatial composition (the abundance and diversity of land use classes), and of spatial configuration (the specific spatial arrangement) (Duarte et al., 2018). For instance, water purification is positively influenced by larger edge density and higher percentage of land use classes whose vegetation acts as a filter for nutrients and pollutants (Gémesi et al., 2011; Qiu and Turner, 2015; Clément et al., 2017). Pollinator and pest control species react positively to high connectivity of habitat patches (Keitt, 2009; Puech et al., 2014). Furthermore, high edge density facilitates spillovers of those agent species between semi-natural habitat and agricultural land (Blitzer et al., 2012; Martin et al., 2016) and thereby improves the delivery of pollination services to agriculture. The aesthetic value of landscapes is amplified by high diversity and high shares of natural land uses, since such landscapes are perceived as beautiful and scenic by humans (Frank et al., 2013).

However, if spatial landscape design is to be utilized to counteract biodiversity and ecosystem service loss induced by agricultural intensification, the interplay of the intensity of agricultural practices and spatial patterns that are relevant for ecosystem services should also be addressed. For instance, policymakers in intensive-agriculture regions may want to support biodiversity by investing in landscape elements. These might not have enough of a positive effect under the present conditions, if they are not created in a larger network. This interaction as well as other landscape-scale measures are still underrepresented in agroeconomic models, farmers' decision-making and policy implementation (Falco et al., 2021; Seppelt et al., 2020). Previous studies have investigated the connections of selected ecosystem services to single aspects of intensification, either the intensity of agricultural practices (van der Plas et al., 2019), or the spatial properties of agricultural fields (Hass et al., 2018) and natural and semi-natural habitats (Kormann et al., 2015). While these studies show progress in acknowledging the spatial nature of intensification and its influences on ecosystem services, reviews have identified gaps regarding the "multiplicative effects of land-use intensity [.], in conjunction with landscape patterns, for ecosystem service relationships" (Qiu et al., 2021). One reason for this gap is that including agricultural intensity adds to the complexity of spatial arrangement interactions, especially since the effects of landscape configuration are also not sufficiently understood yet (Seppelt et al., 2016). In summary, the intricate matter of agricultural intensity influencing ecosystem services in interplay with landscape configuration and composition is still to be explored further. Our study extends the previous research by analyzing the response of a given ecosystem service to the spatial characteristics of a landscape under different levels of agricultural intensity. We test these interactions methodically for different spatial scales, as many ecosystem services are driven by processes emerging on a specific scale (Spake et al., 2019). With that we aim to identify the spatial layout contexts where ecosystem services can be sustained in landscapes of high- or low-intensity agriculture through incorporating the effect of spatial layout on ecosystem service performance, conditional to local agricultural intensity.

We perform our analysis using the Netherlands as a case study, where arable, livestock and horticulture farming is practiced in different spatial settings regarding the landscape composition and configuration. Furthermore, the availability of high-quality national data on the present spatial layout, farming intensity, and ecosystem service indicators allowed us to build knowledge on todays' circumstances that can inform potential agricultural reorganization in the future. Hence, for four important ecosystem services, we ask:

To what extent does agricultural intensity affect the direction and strength of the relationship between spatial composition and configuration metrics and the ecosystem services?

We address this question by using spatial composition and configuration metrics as well as an agricultural intensity index as explanatory variables for the selected ecosystem services data. We discuss the changes in ecosystem service performance under given spatial arrangements in the Netherlands with increasing agricultural intensity at different spatial scales. With that, we integrate knowledge from small-scale studies and put the interacting effects of land use structures and agricultural intensity into a landscape perspective. This understanding is highly relevant for anticipating under which conditions landscape management measures can enhance ecosystem service performance. For instance, the integration of natural elements, the creation of finer-grained landscapes and increased crop heterogeneity have been suggested to buffer the negative impacts of intensive agriculture (Martin et al., 2019; Sirami et al., 2019; Rieb and Bennett, 2020). However, as intensive agricultural practices can also harm adjacent natural ecosystems (Smart et al., 2006), it needs to be determined at which agricultural intensity levels and given amounts or configuration of natural elements ecosystem services benefit effectively. Furthermore, our study helps to indicate for which specific ecosystem services agricultural extensification or changes in the applied practices can be more efficient than changing the landscape layout.

2. Materials and methods

2.1. Agricultural intensity index

We calculated the agricultural intensity index by averaging four normalized indicators that represent measures to increase agricultural output. The first indicator, total Nitrogen application (in kg $ha^{-1}yr^{-1}$) on all crop types, was estimated by the INITIATOR model and based on livestock-specific excrement production, local manure application and redistribution, as well as on legal regulations of artificial fertilizer use (Kros et al., 2019). As the INITIATOR model calculates nutrient fluxes influenced by agricultural management, it has been utilized to evaluate the effect of policy measures and climate and socio-economic scenarios for the Netherlands (Kros et al., 2011; Reidsma et al., 2015). The second indicator, livestock density, was derived from the 2018 Dutch annual census. The spatially explicit data from this farm business survey is provided in the Geographic Information System Agricultural Companies (GIAB) data base (Gies et al., 2015). The livestock numbers from each farm were converted into livestock units, which is a method to aggregate different livestock species counts based on their feed requirements. The conversion factor for each livestock species is set with regards to one adult dairy cow as the reference unit (NVWA, 2019). The livestock units were then connected to the agricultural fields that are maintained by the respective farm. The remaining two indicators are the pesticide application (in kg $ha^{-1}yr^{-1}$), and the share of surface where tillage is used (in %) per crop. The data was taken from records of the Dutch Central Bureau of Statistics (CBS, 2022a; b). The reported pesticide application and the share of "tilled" surface were assigned to the crops listed per agricultural field from 2016 to 2020, which were then averaged to account for crop rotation from year to year. The crops that were not explicitly listed in the CBS data, but are known to receive pesticide application or tillage, were assigned averaged values from CBS data inputs of a similar crop type, e.g. flower bulbs, leafy vegetables, root vegetables, oilseed, or cereals. In order to use the agricultural intensity index together with the spatial metrics, we calculated the focal average intensity within the respective moving window radii or hydrological unit.

2.2. Spatial metrics calculation

We calculated spatial composition and configuration metrics from the 2018 Dutch national land use data (Hazeu et al., 2020) of 50 m resolution using the Fragstats software, version 4.2.1 (McGarigal, 2015).

We summarized the land use data into eight classes in order to represent different land cover and ecosystem types with the spatial metrics: crops, pasture, urban, rural, water, forest and high vegetation, grass and shrub vegetation, and wetland vegetation. To also illustrate broader spatial patterns that have been found to drive ecosystem service performance in current literature (Kormann et al., 2015; Clément et al., 2017; Hass et al., 2018; Martin et al., 2019), we added two aggregated land use classes with more comprehensive definitions: The class "natural and semi-natural areas" incorporates all forests, grass and wetland vegetation, and the class "agricultural fields" combines arable crops and pasture. Throughout the manuscript, we refer to natural and semi-natural areas and natural land uses as descriptors of the areas that were aggregated under the abovementioned classes for the purpose of calculating the spatial metrics for these areas.

We selected spatial metrics due to their reported relevance for our selected ecosystem services and omitted collinear metrics identified by Pearson correlations. The final set includes Shannon diversity of land cover and landscape patch density as metrics describing the overall landscape structure (mentioned in Gémesi et al., 2011; Frank et al., 2013; Duarte et al., 2018; Qiu, 2019). We further used percentage, edge density, cohesion, average patch distance and patch area for the land use classes agriculture, forest, grassland, wetland and natural vegetation in general (see for instance Lamy et al., 2016; Clément et al., 2017; Martin et al., 2019; Uroy et al., 2019; Tscharntke et al., 2021). Percentage of urban and semi built-up land cover was calculated as well with regards to its relevance for landscape appreciation (Fry et al., 2009) and water quality indicators (Qiu and Turner, 2015).

It is important to acknowledge the spatial scale of relevant processes when trying to detect the influences of spatial metrics on ecosystem services correctly (Spake et al., 2019). Therefore, we chose multiple scales to calculate the spatial metrics and inspected in our results how scale influences the interactions between agricultural intensity and the spatial metrics. We utilized the moving window calculation, which estimates the spatial metric for each raster cell from the surrounding landscape within a window of a given radius. We decided on a 500 m, 2500 m and 5000 m radius to cover the movements of different mobile species and humans. For instance, the foraging of solitary bees can happen within a radius of 500 m (Gathmann and Tscharntke, 2002), while touristic recreation takes place within a 5 km radius (Ridding et al., 2018). We added a radius of 2500 m for intermediate ranges of the diverse species groups within the used species richness data set (Nationale Databank Flora en Fauna, 2017). The appropriate scale for water-related services is the watershed or sub-watershed (Syrbe and Walz, 2012; Clément et al., 2017), so we utilized the hydrological units of the Netherlands (Groenendijk et al., 2016) to calculate the spatial metrics within them.

2.3. Ecosystem service indicators

We utilize Dutch national datasets of ecosystem service indicators that are specifically relevant to the rural landscape in the Netherlands. Indicators for food production or carbon sequestration services were not included due to missing evidence for large influence of landscape configuration on their performance (Grêt-Regamey et al., 2014). The used indicators are:

- Species richness, as a score for the amount of species observed within 1 km^2, including vascular plants, amphibians, reptiles, fish, butterflies, dragonflies and birds (Atlas Natuurlijk Kapitaal, 2017; Nationale Databank Flora en Fauna, 2017);
- Potential pollination (in %), as the probability of an area unit being visited by pollinators that disperse from suitable habitats (Nationaal Georegister, 2016);
- Nitrogen and phosphorous concentrations (in mg l^{-1}) measured in surface water bodies and attributed to the sub-catchment area that pertains to the respective water body (Groenendijk et al., 2016);
- Landscape appreciation, a modelled score based on naturalness, historical distinctiveness, relief, urbanity, skyline disturbance and noise level, and calibrated with survey findings (Roos-Klein Lankhorst et al., 2011).

For these indicators, we looked for national field observations or measurements in order to ascribe our results to causal relationships. However, for potential pollination and landscape appreciation, no such data was available, hence we referred to these modelled variables that are partly based on land use data. We examine and discuss the possible correlations between spatial metrics of those land uses with the respective service indicator to clarify their influence on the main subject of this study, the interactions between agricultural intensity and spatial metrics. Species richness is a biodiversity attribute, which itself is not an ecosystem service according to the Millennium Ecosystem Assessment (MEA) classification or the Common International Classification of Ecosystem Services (CICES), but it is widely understood to underpin many ecosystem services (Harrison et al., 2014). Finally, nitrogen and phosphorous concentrations are proxies for the performance of water purification services in a landscape under human activities. Maps of the ecosystem service indicators and further details can be found in the Supplementary Material S2.

2.4. Statistical analysis

We calculated Pearson correlations between the spatial metrics, the agricultural intensity index, and the ecosystem services in order to sort out collinear metrics and detect one-to-one relationships that set the context for the interactions. The correlation coefficients were comparable for all scales and can be found in the Supplementary Material S1.

The spatial metrics and the agricultural intensity index served as predictor variables in the regression models constructed for each ecosystem service (Fig. 1). We utilized Generalized Linear Mixed Models with Gaussian and Gamma error distributions according to the ecosystem service indicator data. We used spatial regression models to account for spatial autocorrelation. In the regressions featuring spatial metrics derived from the hydrological units we used a spatial error model to address a units' dependence on neighboring sub-watersheds. For the regressions with spatial metrics calculated by moving windows we used a Matern covariance structure. The models built for each spatial metric have the following formulas:

$$\text{Single variable } model: \\ Y = \beta0 + \beta1X1 + \mathrm{Matern}(1|x + y) + \varepsilon$$

$$\text{Addition } model: \\ Y = \beta0 + \beta1X1 + \beta2X2 + \mathrm{Matern}(1|x + y) + \varepsilon$$

$$\text{Interaction } model: \\ Y = \beta0 + \beta1X1 + \beta2X2 + \beta3X1X2 + \mathrm{Matern}(1|x + y) + \varepsilon$$

with X1 being the respective spatial metric, X2 standing for the intensity index, βi representing the variable and intercept coefficients, $x + y$ showing the spatial effect and ε being the model residual.

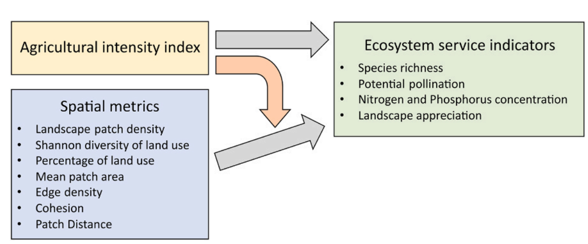

Fig. 1. Conceptual framework of the interaction (red arrow) between the agricultural intensity index and the spatial metrics with regards to their influence (grey arrow) on the selected ecosystem service indicators.

If the interaction term (the product of the agricultural intensity index and landscape metric) significantly contributes to a model in which its individual components were already included, this supports the hypothesis that the relationship between the spatial metric (X1) and the ecosystem service (Y) varies for different degrees of intensity (X2). The regression models are not intended to provide the best prediction of the ecosystem service variation nor to include all relevant predictors, but to help understand the individual effect and the interaction among the predictors.

Calculating the spatial metrics for each raster cell with a moving window resulted a very large dataset due to the resolution and the nationwide extent. To enable the spatial regression model for a meaningful number of cells and to preserve the sensitivity of the significance test, we ran 1000 regressions of 1500 randomly sampled data points for each model. The sample size was chosen to represent the variations in the explanatory variables and the response variable. The regression results were compared using the Akaike information criterion (AIC) and significance tests. We checked if the *interaction model* had a lower AIC than the *addition model*, to make sure that including the interaction term would bring the model closer to the theoretically "best" model, which fits the data perfectly (Burnham et al., 2011). The results of all performed regressions can be found in the Supplementary Material S3. We conducted the entire analysis in the R statistical language (R Core Team, 2021).

3. Results

Our regressions showed that increasing agricultural intensity affected the strength and ultimately direction of the relationships between a spatial metric and an ecosystem service indicator in several different ways. The diagrams in Fig. 2 illustrate for which spatial metrics agricultural intensity amplified, reversed or mitigated their effect. Interactions between spatial metrics and agricultural intensity were mostly consistent across all scale levels at which the metrics were calculated (see Supplementary Material S3). As the highest diversity of interaction types is present in the results for the 2500 m radius, we chose to present this scale below. Differences between the scales are limited to a few cases. The influence of scale on the number and types of interactions identified will be addresses in more depth in the discussion.

For landscape appreciation, the beneficial effects of natural areas, mostly forest or grassland, increased with stronger agricultural intensity. Distance between natural patches was not positively related to landscape appreciation, but with increasing agricultural intensity this relationship was weakened. The loss of this cultural service associated with more urban or rural land use was less pronounced in intensive agriculture areas. Lastly, increasing levels of agricultural intensity enhanced the negative influence of agricultural land cover on this service.

No significant interactions were found in the regressions performed for nitrogen concentration at almost all scales. In contrast, for phosphorus concentration in surface water, more interactions were found across scales. As shown in Fig. 2, patchier and more diverse landscapes were no longer associated with lower concentration values when the agricultural intensity in the surroundings increased. Higher agricultural intensity amplified the nutrient-reducing effect of larger forest patches.

In the case of potential pollination, we accounted for the inverted link function of the Generalized Linear Model with Gamma error distribution in order to interpret the interactions correctly. The negative impacts of a large surface area of agriculture in the landscape were aggravated if the intensity increased. Further, the positive effect of grassland structures on potential pollination became more apparent in landscapes of higher agricultural intensity. In addition, shares of rural and urban areas increased pollination, which was also amplified by higher agricultural intensity in the surroundings.

Higher agricultural intensity levels reduced the positive effect of a diverse landscape and cohesive nature on species richness. The positive influence of wetland and grassland- vegetation or generally natural areas was amplified when agricultural intensity increased. In addition, the regressions showed that for the Netherlands the percentage of agricultural land use had a negative effect on species richness, which was enhanced by higher agricultural intensity. Lower species richness tended to be found at sites with large forest patches, but with higher agricultural intensity this relationship was inverted.

For all interaction types that are illustrated in Fig. 2, the line graphs in Fig. 3a-h display examples of how the relationship between an ecosystem service indicator and a given spatial metric changes under different levels of agricultural intensity. First, in Fig. 3a, landscapes appreciation in low-intensity agricultural landscapes decreased strongly with more urban land use. In highly intensive landscapes, this effect was reversed. In contrast, natural vegetation edges improved landscape appreciation, even more so in intensive agriculture areas (Fig. 3b). For phosphorus concentration (Fig. 3c), we observed that high patch density becomes associated with high concentration when agricultural intensity is increased. Across all forest patch sizes, the phosphorus concentration stayed rather constant for low agricultural intensity, while landscapes with larger forest patches had lower concentration levels under medium agricultural intensity (Fig. 3d). In the case of potential pollination, the larger the percentage of agricultural land and the higher the agricultural intensity, the lower the pollinator visitation (Fig. 3e). Correspondingly, low- and intermediate-intensity sites had for the most part higher service performances, yet, with very high shares of grassland vegetation, sites with high-intensity agriculture also exhibited similar chances for pollination (Fig. 3 f). Species richness decreased in landscapes with larger forest patches, but this effect was reduced once the agricultural intensity increased (Fig. 3 g). Finally, highly cohesive natural elements embedded in a matrix of very intensive agriculture could not achieve the same species richness as landscapes of low-intensity agriculture (Fig. 3 h).

4. Discussion

4.1. *The benefit of many natural structures for ecosystem services depends on agricultural intensity*

By means of our methodical exploration, we found that increasing the intensity of agriculture resulted in changes in the effect of various landscape structures on ecosystem services throughout all utilized scales. The line graphs in Fig. 3a-h showed that for different ecosystem service indicators, higher percentage, mean area or edge density of natural land uses can greatly increase the ecosystem service performance in landscapes of high-intensity agriculture, but do less so in landscapes with lower agricultural intensity. Our results suggest that the threshold whether reducing agricultural practice intensity or adding natural landscape elements efficiently achieves high ecosystem service performance, depends on the ecosystem service in question. Fig. 3b indicates that increasing the density of natural edges in high-intensity agricultural landscapes can effectively increase the landscape appreciation, as they enhance the perceived variation in land use, which is strongly related to landscape attractiveness and scenic beauty (Uuemaa et al., 2009). The performance of this cultural ecosystem service indicator is therefore not weakened by intensive practices as long as natural landscape elements are present. For potential pollination, only landscapes with very large shares of natural grassland around high-intensity agriculture achieved a similar performance as landscapes of low agricultural intensity (Fig. 3 f). Hence, improving the chances for pollination in the presence of high-intensity agriculture would require an immense increase in the share of natural habitats. In contrast, low-intensity agricultural landscapes show less harmful practices, such as pesticide or artificial fertilizer application (Topping et al., 2015; van der Plas et al., 2019), but the availability of natural elements as habitat and forage resource is crucial. For species richness, the benefits of strong cohesion of natural land use were erased under high-intensity agriculture (Fig. 3 h). Cohesion, as an expression of physical connectedness

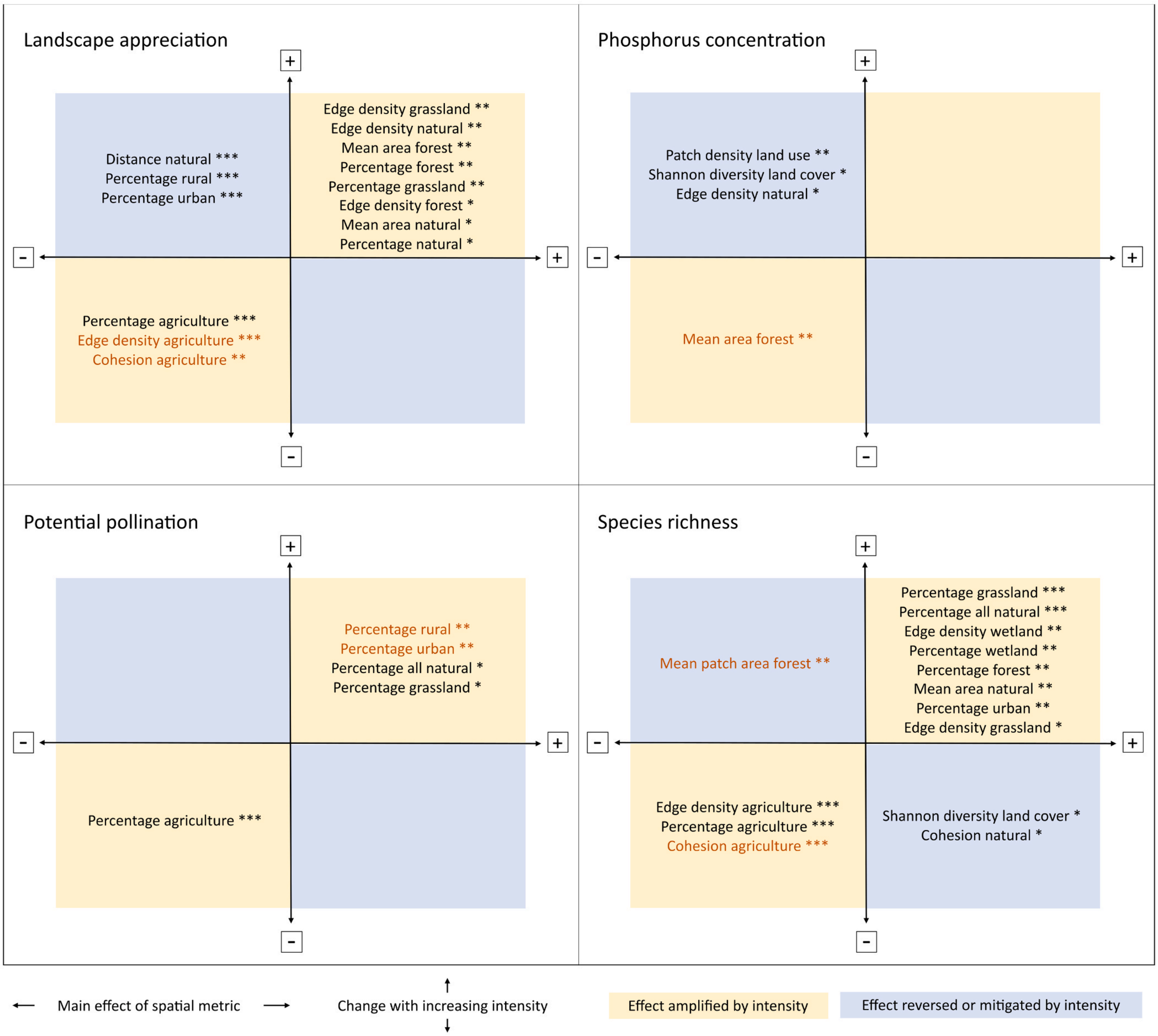

Fig. 2. Effects of increasing agricultural intensity on the relationship between ecosystem service indicators and spatial metrics calculated within the 2500 m radius. The x-axes depicts the main effect of the respective spatial metric (positive or negative) and the y-axis depicts the interaction effect. Boxes in blue contain spatial metrics for which the main effect was reversed or mitigated by increasing agricultural intensity. Yellow boxes contain spatial metrics for which the main effect was amplified by increasing agricultural intensity. The significance levels of the interaction effects are marked with * ** for $p < 0.001$, * * for $p < 0.01$, and * for $p < 0.05$. The spatial metrics marked in red do not have a significant ($p < 0.05$) main effect.

(McGarigal, 2015), did not shelter the habitat from the detrimental effects of intensive land use, such as the combination of nitrogen deposition from livestock, agrochemicals and changes in soil structure (Hunziker and Kienast, 1999; Leip et al., 2015). We presume that depending on the particular processes that drive the individual ecosystem service indicator, high-intensity practices can damage the natural land uses in a particular spatial configurations so that they cannot alleviate the negative impacts of intensive agriculture. In sum, for ecosystem services depending on habitat vulnerable to changes in abiotic conditions triggered by agricultural practices, our results support the notion that the spatial arrangement of natural land uses needs to be carefully matched with as little as possible application of agrochemicals in agriculturally dominated landscapes.

4.2. *Driving processes of ecosystem service performance determine which interactions can occur*

We observed several interactions that allow us to contemplate how ecosystem service-specific processes dictate for which spatial metrics their effect changes under different agricultural intensity levels. For instance, agricultural intensity had limited influence on the mitigation effect of differently sized forest patches on surface water phosphorus concentration. Hence, other spatial arrangement factors like the location of those forest patches relative to the stream could be utilized to optimize success of nutrient sink patches (Gémesi et al., 2011). Furthermore, land use diversity and patch density were only favorable to lower phosphorus concentration in surface waters in low-intensity agricultural landscapes (Fig. 3c). In turn, nutrient pollution could not be retained in heterogeneous landscapes that feature high-intensity agriculture, potentially due to the higher overall nutrient input (Clément et al.,

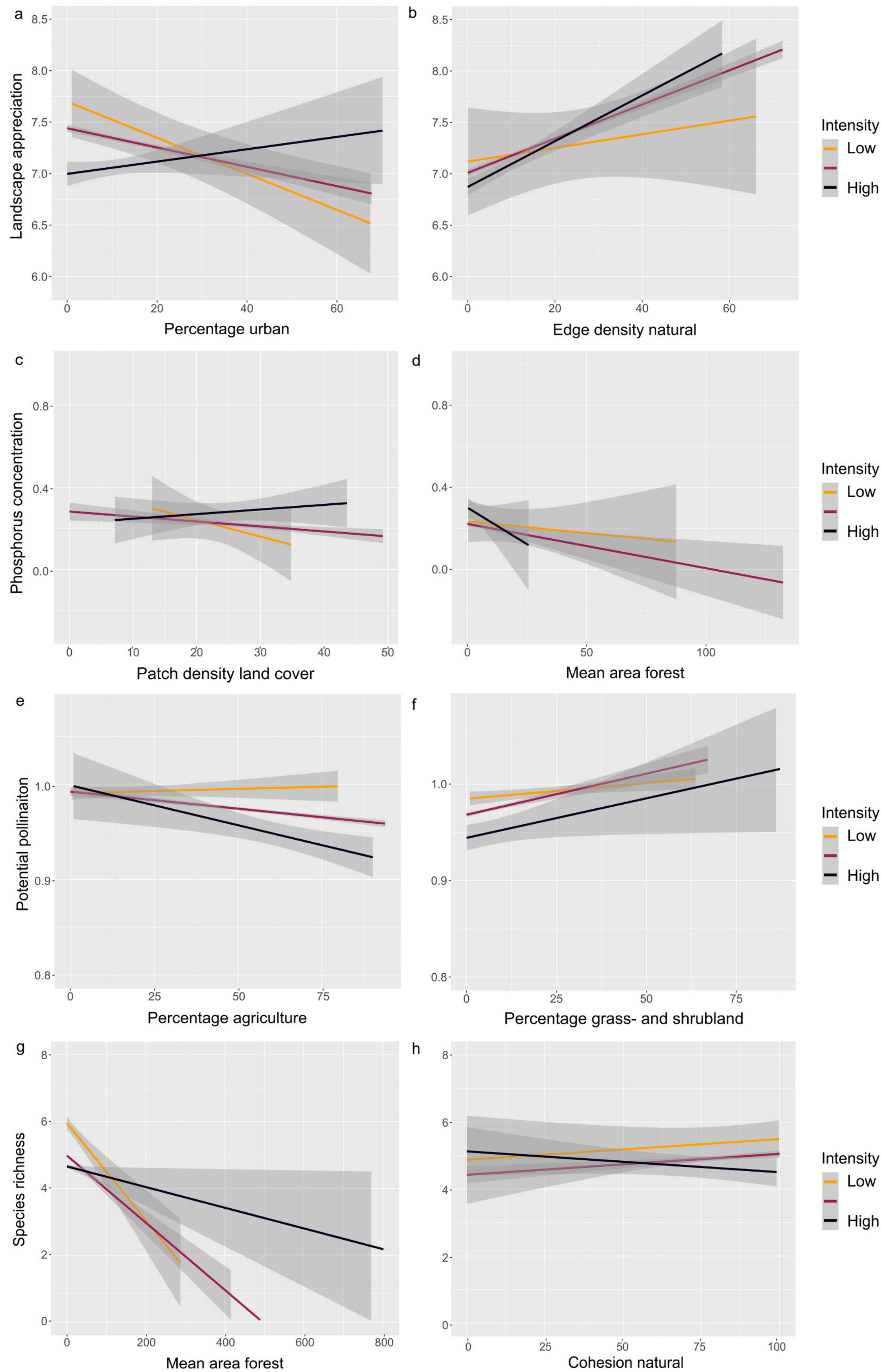

Fig. 3. a-h: Changes in the relationships of the ecosystem services with spatial metrics through different levels of agricultural intensity. The levels were defined using the standard deviation of the agricultural intensity index value range. The grey shadows mark the 95% confidence bands.

2017). In contrast, the positive effects of land use patch density and diversity on landscape appreciation were not significantly altered by different agricultural intensity levels in the surroundings. We may argue that people perceive heterogeneous landscapes as attractive (Uuemaa et al., 2009; Duarte et al., 2018), but do not recognize agricultural intensity when they judge landscapes based on their diversity of land use types. Urban and rural areas can also interact with intensive agriculture, due to the individual requirements of the ecosystem services. In our study, potential pollination and species richness increased in landscapes with more urban and rural settlements when the agricultural intensity in the surroundings increased, perhaps due to important habitat being provided in cities for species that avoid intensively managed agriculture (Goertzen and Suhling, 2015; Hall et al., 2017). Species richness also tended to be lower in sites with larger forest patches, potentially due to the disturbances of forest management and the altered tree species composition driving away species with other requirements (Paillet et al., 2010).

4.3. Interactions are shaped by the studied landscape settings and available data

We observed the respective effects of percentage of agriculture, mean area of agriculture, edge density of grassland or percentage of natural land uses on the ecosystem service indicators were amplified with higher agricultural intensity throughout the regressions. These metrics are also the ones that partly correlate with the agricultural intensity measure, positively or negatively. This relates to the landscape structures found in the Netherlands, where high agricultural intensity tends to coincide with homogeneous landscapes that are dominated by large fields and lack edge density of natural grass- and wetland vegetation. In turn, landscapes of low agricultural intensity are more interspersed with natural structures. The correlations might have increased the chance of a significant interaction in the regression models, however, the spatial metrics and the agricultural intensity index did not coincide to the extent that we had to expect a non-linear effect of one of the variables instead of a true interaction.

In some cases we found strong correlations between the explanatory variables and the ecosystem service indicators. For instance, our results reflect the dependency of species richness on the availability and quality of habitat (Qiu et al., 2021; Tscharntke et al., 2021). However, we observed the strongest correlations for landscape appreciation and potential pollination with metrics describing spatial patterns of natural vegetation. These service indicators were produced by models that included land use as a predictor, hence, those spatial metrics inherently contribute to the performance of the service indicators. Therefore, the found relationships have to be interpreted with caution. As no empirical measurements were available for the concerned ecosystem services at the Dutch national scale, we focus in this study on revealing the interactions among the predictor variables instead of fitting models that best predict the ecosystem services.

For nitrogen and phosphorus concentration, we did not observe the relationships we expected as agricultural input reportedly increases nutrients in surface waters (Qiu and Turner, 2015; Wassen et al., 2021). Apparently, our intensity index did not address all the important biochemical processes driving the nutrient load in surface waters. It is possible that higher resolution data on the local tillage and fertilization system is necessary at this spatial scale, as Clément et al. (2017) noted. Likewise, we anticipated both indicators would negatively correlate with patchy landscapes, grassy edges and forest patches as these structures provide sinks to mobilized nutrients (Thomas et al., 2020). Yet, phosphorus concentration behaved as expected, but nitrogen concentration showed reverse relationships with many of said spatial metrics. The different behavior of nitrogen and phosphorus could be related to differences in their mobilization and transport as noted by Gémesi et al. (2011).

4.4. Changes in scale rarely affect the observed interactions

The direction in which the effect of spatial metrics was driven by agricultural intensity (mitigating vs. amplifying) rarely changed across the different metrics calculation windows. Metrics that describe similar landscape structures had the same types of interaction with agricultural intensity throughout the scales. This could be related to a more or less constant relationship between the patterns created by the spatial metric calculation and the focal average of the intensity index. The consistency of the found relationships is also mirrored in the similar correlation coefficients for all scales. It can be noted that for potential pollination, the most interactions appear at the 500 m scale. This seems to be connected to the smaller radius of pollinator foraging movement (Gathmann and Tscharntke, 2002). Species richness showed the most interactions at 2500 m, which represents an intermediate movement range that perhaps matched the diverse species groups that are included in this dataset (Atlas Natuurlijk Kapitaal, 2017). For landscape appreciation, the interaction patterns changed rarely, yet, in the 500 m radius and the hydrological units, the positive effect of cohesive natural patches was diminished by higher agricultural intensity. We can hardly explain this scale-specific behavior with known characteristics of the used dataset. For nitrogen concentration, agricultural intensity only interacted significantly with spatial metrics at the level of the hydrological units. Similar to the correlation coefficients, these interactions did not match our expectations. Perhaps, the scale of the nitrogen concentration measurements in surface waters did not correspond with our spatial metric calculation extents. It is also not clear, which processes have driven phosphorus concentration at different scales, because the effect of natural edge density was either amplified or reversed with higher agricultural intensity. The interactions picked up at the hydrological units potentially show the most expected relationships, as this is the scale where the concentrations have been measured. With our findings, we hope to encourage future research to do multi-scale field studies in order to refine the knowledge on the influence of spatial scale on interactions of landscape structure and agricultural intensity.

4.5. Implications for research and practice

Existing research and landscape management approaches have addressed the effects of spatial layout on ecosystem services to produce spatial scenarios for strategically planning of sustainable agriculture. We advocate to include agricultural intensity as an interacting factor in such scenarios to create a successful tool for the creation of policy guidelines that are close to the farming reality. According to the patterns we found for the Netherlands, species richness in well-connected habitats need to be protected from the effects of higher pesticide or artificial fertilizer application or deposition from farming in the surroundings. Therefore, only low-intensity farms can be allowed to be located in proximity to such ecosystems. Meanwhile, negative externalities from small islands or strips of high-intensity agriculture can be buffered when combined with sufficient natural areas, while the landscape still provides cultural and pollination services. The distribution of natural buffers and habitat areas could therefore become an explicit requirement for high-intensity agricultural areas. At the same time, our findings suggest to reduce agricultural intensity, especially in simplified landscapes, in order to recover ecosystem services. The combination of high share of agricultural areas with higher intensity inevitably leads to strong losses in ecosystem service performance at those areas and should therefore be limited through policies. These suggestions target the management and landscape structure of the Netherlands and can help to sustain informed planning decisions that are needed in many Western European countries with similar problems. It is beyond the scope of this study to give indications on particular policies, such as the agri-environmental-climate measures of the EU's Common Agricultural Policy. Based on our results, we could argue that overall ecosystem services return to investments is higher in intensively cultivated landscapes, so it would be best to allocate funding towards more natural elements in these landscapes. On the other hand, funds targeted at general de-intensification would have a similar, if not better, effect when less intensively managed landscapes perform better than the intensively managed landscapes regarding multiple regulating and cultural ecosystem service. To investigate what would be the best way to spend the funds, research on the costs and benefits of the various options for farmers would be needed.

In future research, we recommend to further investigate the ecosystem services' behavior with different farming practices and controlled variation in spatial arrangements. We further encourage the use of empirical data and relevant ecosystem services indicators. As this study addresses a variety of service indicators at the Dutch national scale, we decided to utilize a more holistic agricultural intensity index, following the example of Herzog et al. (2006), Turner, Doolittle (2010) and van der Plas et al. (2019), instead of selecting an index that addresses single agricultural practices such as artificial fertilizer usage (see Kleijn et al., 2008; Qiu et al., 2021). In studies with smaller spatial extent, specific practices applied to only arable crop fields or to pastures such as mowing, tillage, manure or pesticide application should be looked at separately to achieve results than can contribute better to predictions. For service indicators related to water quality, the hydrological settings and soil types should also be included, since the behavior of nutrients in soils, during transport and in water bodies and sediments is governed by a complex interplay of soil and water chemistry, as well as physical transport processes (van Der Grift et al., 2016). After identifying interactions of relevant spatial metrics with the surrounding agricultural intensity, we also argue that these interactions should be incorporated more into mapping and modelling tools to improve the predicted ecosystem services performance. For instance, the calculation of the impact of agricultural practices on a given species' habitat can be adapted according to the spatial configuration of natural land uses in the surroundings.

5. Conclusion

In this study, we investigated the interactions of agricultural intensity with spatial composition and configuration metrics that are known to drive ecosystem service performance. We established that agricultural intensity affects not only landscapes that are dominated by agricultural fields or share boundaries with this land use. We also found that agricultural intensity can influence processes relevant for the ecosystem services in well-connected nature areas or in landscapes with considerable amounts of urban areas. We showed that the negative impacts of high-intensity agriculture can be buffered with certain amounts and spatial arrangements of natural land use, though we emphasized that landscapes dominated by agricultural areas often cannot support high ecosystem service performance under increasing agricultural intensity. Since we were not able to draw conclusions for all utilized ecosystem service indicators, we advocate for more inclusion of different agricultural practices in landscape ecological research. In sum, our results could help to optimize ecosystem service modelling, as well as give starting points for management recommendations of spatially planning farmland. For the Dutch example, our approach could be utilized to create regional scenarios with optimal combinations of agricultural intensity patterns and land use arrangement.

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.

Data Availability

Data will be made available on request.

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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.agee.2023.108692.

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