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# Supporting stakeholder dialogue on ecosystem service tradeoffs with a simulation tool for land use configuration effects

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ABSTRACT

Various approaches are available to assist stakeholders in identifying and resolving ecosystem service tradeoffs. However, existing tools fall short in simulating land use configuration effects on ecosystem services and subsequently making these effects accessible to users with varying levels of expertise. To address this gap, we introduce PLACES, a tool that estimates land use impacts on multiple ecosystem services by incorporating landscape-level processes. Tool results are provided in real-time and visualized to support a dialogue between different stakeholders. This study presents the tool development and application during a mixed stakeholder workshop, after which mental models, questionnaires, and videos were analyzed to evaluate PLACES. The tool increased the participants' understanding of insights of spatial processes and sparked discussions on the societal goals for sustainable landscapes. For future applications of PLACES, we encourage careful tailoring of the landscape representation and land use impact simulations to match the knowledge of the respective users.

## 1. Introduction

Landscapes are complex socio-ecological systems that host many interacting components and processes (Parrott and Meyer, 2012). For instance, wildfire intensity, soil nutrients, grazing, and plant productivity closely interact in grassland ecosystems (Reinhart et al., 2016), whereas floodplains are often characterized by the interplay of seasonal precipitation, forest cover, and fishery (Arantes et al., 2019). Landscape complexity becomes especially apparent when decision-makers try to balance multiple, and at times conflicting, demands for ecosystem services, such as agricultural production and habitat provision (Andersson et al., 2015). Ecosystem services are influenced by a plethora of factors, many of which are tied to the spatial arrangement of land management practices (Fisher et al., 2009). Land use effects on ecosystem services that extent beyond the respective land patches (i.e. spatial spillover effects or spatial externalities) are not easy to comprehend and communicate (Assis et al., 2023; Metzger et al., 2021). Moreover, specific land use practices often prompt tradeoffs between ecosystem services. Agricultural land use in the Netherlands is a prominent example of such tradeoffs, as agricultural production is highly optimized for export, while soil and water quality, as well as biodiversity, are rapidly declining (Vermunt et al., 2022). The environmental degradation caused by intensive agriculture is perceived differently by involved stakeholders, leading to intense political disputes, societal upheavals, and farmer protests (van der Ploeg, 2020). To restore social cohesion and implement sustainable land use measures, cooperation between stakeholders with different perspectives is required (Remkes et al., 2020; Tisma and Meijer, 2018). Participatory approaches that evaluate spatial scenarios with stakeholders have been found successful for this aim (van Hardeveld et al., 2018; van Mulken et al., 2023). To assist these approaches, tools are needed that facilitate both the understanding of land use effects and a dialogue on tradeoff solutions (Duarte et al., 2020; Young et al., 2014).

Although a multitude of tools with different purposes exists (Grêt-Regamey et al., 2017), they rarely calculate land use configuration effects on ecosystem services and utilize these results to facilitate

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stakeholder communication. For instance, ecosystem service tradeoffs in different land use scenarios are illustrated in multi-criteria decision analysis (MCDA) applications (Vogdrup-Schmidt et al., 2019). While stakeholder preferences are integrated in MCDA approaches, local variations in ecosystem service performance caused by biophysical conditions are rarely acknowledged. In contrast, many ecosystem service mapping tools may incorporate high-resolution land cover data to account for local biophysical characteristics, but fail to capture important landscape-level processes like spillover, or proximity, or edge effects (Metzger et al., 2021). Specific tools like InVEST or ARIES simulate spatial processes and consider land use effects that reach beyond their location (Natural Capital Project, 2023; Villa et al., 2014). However, the applied calculations and resulting ecosystem service maps require additional interpretation before stakeholders can use them to discuss the impacts of land use allocation on ecosystem services. To address spatial planning questions with stakeholders of different expertise, complex ecosystem service data needs to be operationalized (Brunet et al., 2018; Rosenthal et al., 2015).

In response to the drawbacks of existing applications, we designed PLACES (Participatory Landscape Configuration Effects Simulator), which combines the strengths of available approaches. Our novel tool simulates landscape-level processes such as nutrient leaching, air pollution, or groundwater level changes, and visualizes the land use impacts on ecosystem services performance in a comprehensible way for users with various backgrounds. PLACES provides real-time responses to land use scenarios designed by the users, facilitating a dialogue among them. The tool aims to help users comprehend how local land use practices interact with biophysical conditions and the spatial context of other land uses and in driving ecosystem service provision. PLACES also provides a basis for debates on landscape-wide multifunctionality and ecosystem service tradeoffs.

PLACES is designed to be adaptable to various landscape planning contexts. In this study, we present the development and application of PLACES for a case study on the functional tradeoff between agricultural productivity, ecosystem health and human wellbeing in the Netherlands. During a mixed stakeholder workshop, we apply PLACES

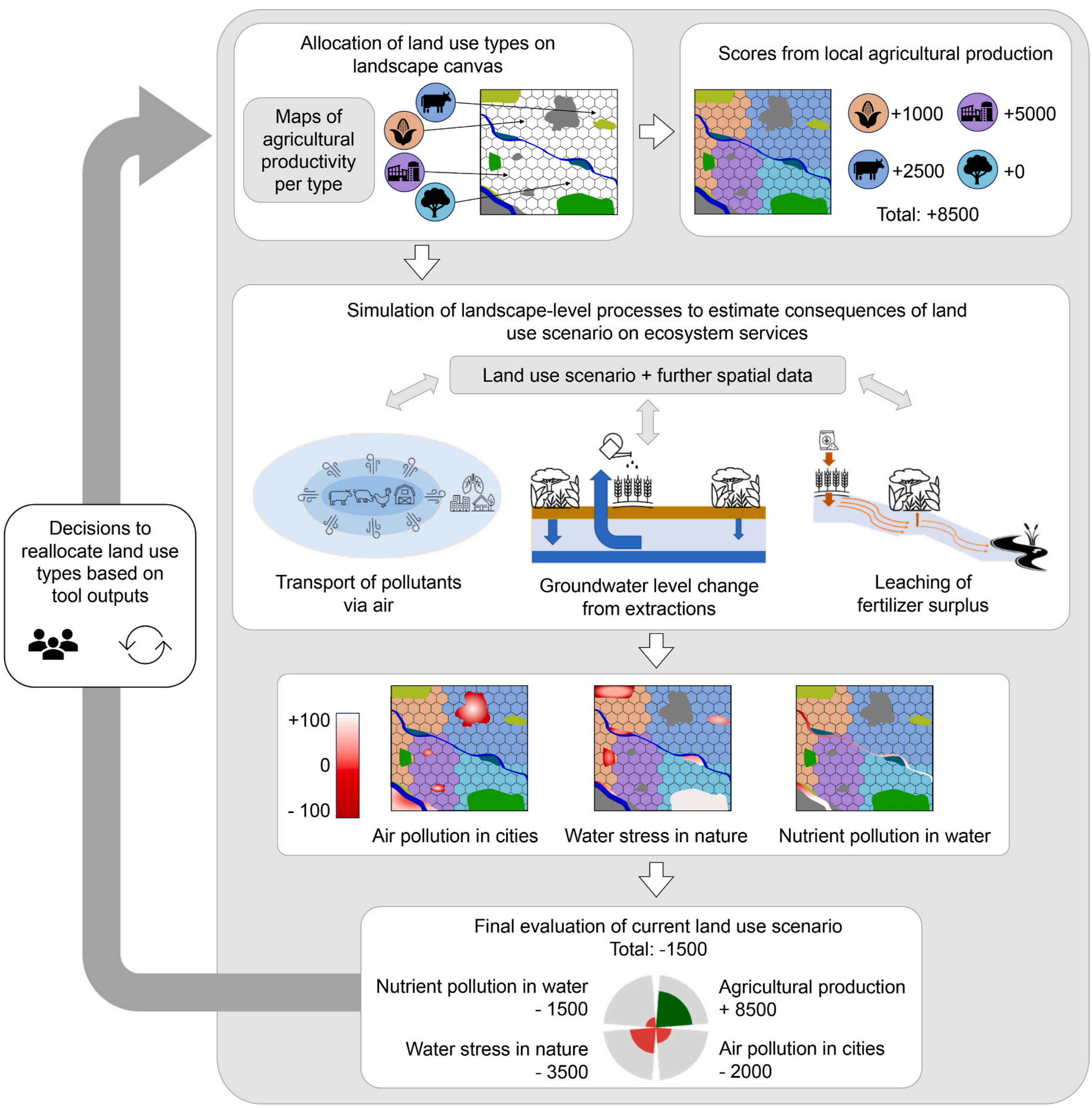


**Fig. 1.** Illustrative example of the functionality of PLACES. Users start by allocating land use types into a landscape canvas using maps of the local agricultural production of each land use type. Scores are instantly displayed. Models calculate the ecosystem service responses by simulating landscape-level processes on the designed land use map. Maps, a score table, and a graph support the users in their decisions to reallocate the land use types.

to facilitate a discussion among farmers, citizens, business owners, scientific experts, and policy makers at various levels of government. Using the gathered data, we assess whether the participants acquired a deeper understanding of land use effects on ecosystem services by using PLACES as the main tool of the workshop. Furthermore, we elaborate on PLACES' contributions to a discourse among the participants about sustainable spatial planning in Dutch agriculture. Finally, we discuss the design choices and application settings to summarize essential points for further adaptations and extensions of PLACES or similar tools for supporting stakeholder dialogue.

## 2. Methods

### *2.1. General functioning*

PLACES consists of an online application, the front end, in which users can design spatially-explicit land use scenarios, and of a set of models, the back end, which calculate the ecosystem service responses to these scenarios. In an example application of the tool (Fig. 1), the users fill in the blank spaces of a digital 'landscape canvas' with a set of pre-defined land use types. As an orientation, users can rely on maps with the local agricultural productivity from each land use type. The total agricultural production score for the landscape is instantly displayed. Then users submit their land sue scenario to the back end, where an R-script combines it with relevant spatial data, such as soil type, groundwater depth, or vegetation characteristics to simulate processes like aerial transport of pollutants, lowering of groundwater levels in the neighborhood of extraction points, or leaching of surplus nutrients through soil into water bodes. The models specifically consider the location and spatial context of land cover and land management practices, which are key factors for ecosystem services performance (Eigenbrod, 2016; Gebhardt et al., 2023; Qiu, 2019). The resulting maps depict the spatial distribution of ecosystem service losses or gains that are possible with the available land use types. The script also produces a graph that illustrates how the current land use scenario performs compared to each services' best- and worst-case scenario, along with ecosystem services scores of the total landscape. The tool users can now utilize the outputs visualized in the online interface to deliberate how to reallocate the land use types for better scores. Depending on the intended use of PLACES, the landscape can be optimized for specific ecosystem service targets, or several targets can be balanced. Both the landscape canvas and the model scripts are customizable to different ecosystem services, geographical locations, languages, and temporal or spatial scale, as advocated by Martínez-López et al. (2019).

### *2.2. Tailoring PLACES to a specific context*

We tailored PLACES to support understanding of spatial processes and communication about a 30 km by 45 km agricultural landscape in the Dutch province of Noord-Brabant. In this region, intensive livestock farming has induced several environmental problems, which are locally exacerbated by the urbanization and geomorphological conditions (Provincial government of Noord-Brabant, 2022). Hence, this area represents the challenge of implementing ambitious sustainability targets for agriculture that many other European countries face as well (Bazzan et al., 2023; Fiore et al., 2022). To customize PLACES to this context, we used the simulation game "Tradeoff! Agriculture Edition" as an orientation, as it aims to teach users about the tradeoffs and synergies between agricultural production and other ecosystem services (Verutes and Rosenthal, 2014). In this game, the players rely on maps of a fictional landscape that show at which locations ecosystem services gains and losses can be expected. In contrast to this static approach, PLACES dynamically simulates the spillover effects of land use based on the scenario designed by the users. We further decided to utilize a simplified version of the study area as a canvas to motivate the users to design the most desirable scenario for 'their' landscape.

To represent the relevant system components and processes in PLACES in a meaningful way and at the appropriate level of detail, we extensively consulted local experts. First, we carried out three interactive meetings with practitioners from water boards, cadaster, local businesses, and municipality and province administration to rank which ecosystem services are considered most important in the region and are affected by agricultural land use. Based on this ranking, we selected the most relevant ecosystem services that experience off-site land use effects, namely air purification, water regulation and purification, habitat quality, and recreation. Second, we derived six consequences of agricultural land use for these ecosystem services: air pollution in cities, nutrient pollution in nature, water stress in nature, nutrient pollution in surface waters, habitat fragmentation, and loss of recreational value. Third, we defined five agriculture types as the eligible land use types in PLACES: extensive arable farming, intensive arable farming, extensive dairy farming, intensive dairy farming, and indoor Agroparks specializing in integrated pig, poultry, and vegetable production. All types contribute uniquely to the listed ecosystem service consequences through their crop rotations, agricultural buildings, livestock density, manure and fertilizer application, and groundwater extractions (Table 1). We utilized statistical data from the Dutch agriculture sector and related publications to define the applied practices on both sandy and clay soils, which predominate in the study area (Meer 2022; CBS, 2023; RVO, 2023).

We created maps of the potential agricultural production (0%–100%) for each type to instantly display the in-situ agricultural production score. The potential productivity for the Agropark was set to 100% in areas that are accessible for transport, and are well connected to energy and water sources, as well as to consumers, labor markets, and knowledge institutes. All remaining areas were set to 0% productivity for Agroparks (Wageningen Metropolitan Food Clusters, 2023). The suitability for the arable farms was derived from maps that incorporate the soil and groundwater requirements of arable crops. The suitability for the dairy farms was based on the growth requirements for pasture and feed crops (Remme, 2017). The maximum productivity for the intensive arable and dairy types was set to 25%, as these types were interpreted to be as productive as one quarter of an Agropark (Wageningen Metropolitan Food Clusters, 2023). The extensive arable and dairy types were set to maximum 15% productivity based on the yield gap between the extensive and the intensive farming (De Boer and Van Ittersum, 2018).

### *2.3. Ecosystem service consequence models*

We developed models to create comprehensive maps of land use configuration effects on ecosystem services. To parameterize these models, we reviewed existing ecosystem service assessment methods and consulted experts from both academia and planning practice.

To model air pollution in cities, we chose to simulate emission and transport of particulate matter. We selected PM2.5 as the pollutant due to its adverse effects on human health (WHO, 2016). First, we defined PM2.5 emissions per agriculture type at each location by using reported emission factors for livestock housing, manure management, crop cultivation and harvesting (European Environment Agency, 2019). Next, we modelled the diffusion of PM2.5 with an exponential decay formula that described the reduction of pollution with distance from the emission source (Karner et al., 2010; Requia and Koutrakis, 2018). We omitted factors like wind direction and velocity to focus on the effects of a given landscape configuration.

We modelled nutrient pollution in nature as ammonia deposition, as it is a major driver of biodiversity loss and habitat degradation in European countries with high livestock densities, including the Netherlands (Bobbink et al., 2010; Stevens et al., 2010). We determined ammonia emissions per agriculture type from emission factors of grazing, livestock housing, manure and fertilizer application (European Environment Agency, 2019). Similar to air pollution, we utilized a

**Table 1**
Main characteristics of the five agriculture types defined for the study area.

| | Extensive arable farm | Intensive arable farm | Extensive dairy farm | Intensive dairy farm | Agropark |
|---|---|---|---|---|---|
| Land cover or crop rotations | 50% cereals<br>25% legumes 8.3% potatoes<br>8.3% sugar beet 8.3% onions | 20% potato<br>20% sugar beet 20% winter wheat<br>20% other cereals<br>20% legumes | Pasture<br>Feed crops<br>Stables | Pasture<br>Feed crops<br>Stables | Multi-story greenhouse and stables |
| Animals per ha | 0 | 0 | 1.4 milk cows<br>0.16 beef cattle<br>0.4 sheep | 3.4 milk cows | 9200 pigs<br>96,000 chickens |
| Total N application on sand in kg/ha/yr | 105 | 144 | 96 | 320 | 0 |
| Total N application on clay in kg/ha/yr | 135 | 129 | 96 | 385 | 0 |
| Groundwater extraction on sand in $m^3$/ha | 60 | 150 | 100 | 130 | 0 |
| Groundwater extraction on clay in $m^3$/ha | 30 | 100 | 80 | 100 | 0 |

simplified exponential decay formula to calculate the decreasing amount of deposited ammonia with distance from the emission source (RWS, 2001). We chose not to differentiate the vulnerability of different vegetation types to ammonia deposition to avoid patchy and unreadable maps.

We depicted water stress in nature as the effect of agricultural groundwater extractions that reach into nature areas. For this, we applied distance decay formulae to the amount of groundwater extracted from sandy and clay soils by each agriculture type per year. The distance decay formulae emulated the spread of hydrological effects through the landscape (van der Gaast and Massop, 2003). Small-scale differences in hydrological conductivity of aquifers, aquitards, and cover layers were omitted to ensure the understandability of the model outputs, and limit model calculation time. To account for regional variations in potential water stress, we reduced the final water stress scores in areas of consistently low groundwater levels (van den Eertwegh et al., 2021).

We simulated nutrient pollution in surface water as the leaching of water-soluble nitrogen from agricultural land use into surface waters. First, we defined different leaching masses for each agriculture type on sand and clay soils based on the local nitrogen surplus (Fraters et al., 2012; Lin et al., 2016; Rashmi et al., 2017). Using a digital elevation model (DEM), we divided the area into small sub-watersheds that drain into the surface waters. Finally, for each sub-watershed, we divided the leaching mass by its distance to the surface water and then summed up the resulting values. In sub-watersheds that contained natural land uses, we reduced the final leaching mass based on the vegetations nutrient removal effectiveness (Mayer et al., 2007; Zhang et al., 2010).

For habitat isolation, we calculated a similarity index, which describes the spatial context of a habitat patch within its neighboring patches (McGarigal, 2015). We used a search radius of 2000m to define the neighboring area, with corresponds to the medium dispersal area of a model species (Vos et al., 2001). We determined the hospitality of the present land use classes within the search radius using their degree of naturalness (Steinhardt et al., 1999). The final habitat isolation value per patch was calculated by summing up the area-weighted naturalness value of each patch within the search radius.

We calculated loss of recreational value as a combination of the in-situ recreational value of land uses and the recreational value of their surroundings. The in-situ recreational value for each agriculture type was based on perceived naturalness, skyline disturbance (Roos-Klein Lankhorst et al., 2011), smell and noise (Lautenbach et al., 2011). We selected industrial areas and Agroparks to reduce the recreational value of neighboring areas within a distance of 2500m due to the widely visible buildings and far-reaching perceptibility of smell and noise (Roos-Klein Lankhorst et al., 2011).

### 2.4. Application of PLACES

We applied PLACES during a stakeholder workshop with 23 participants: farmers, researchers, interested citizens, practitioners from governmental institutions, and representatives of local businesses. After a plenary introduction, the participants were split into five groups of mixed stakeholder backgrounds and teamed up with a moderator and a technical staff member who facilitated joint decision-making. In the sessions, the stakeholders were first asked to fill in the landscape canvas with the available agriculture types to create land use scenarios that would achieve a specific threshold for agricultural production. Once they achieved that threshold, PLACES calculated the consequences for ecosystem services from the land use scenario maps. In subsequent rounds, the groups were asked to achieve additional target scores for other ecosystem services, resulting in increasing ecosystem service trade-offs to be accommodated. After several rounds of land use scenarios design and engaging with the resulting consequence maps and scores, the groups prepared a final map and discussed their experience with PLACES. During a debriefing session with all participants, the final maps and scores from all groups were shared to compare the chosen land use allocation strategies.

### 2.5. Evaluation of PLACES

During the workshop we gathered data to evaluate PLACES under three aspects: capacity to quickly and comprehensibly calculate the impacts of the designed land use scenarios on ecosystem services, increase in the users' understanding of spatial processes, and support of dialogue between the users. To achieve the first aspect, the models in PLACES needed to capture relevant factors at an understandable complexity level (Apitz, 2013) and emphasize spatial processes as the functional link between input (land use information) and output (land use impact on ecosystem services) (Hewitt and Macleod, 2017). Moreover, the models needed to be responsive to the spatial configuration implemented by the stakeholder (Metzger et al., 2021), and calculate results at the pace of the users' interactions (van Hardeveld et al., 2019). To verify whether these criteria were met, we video-recorded the sessions with the permission of the participants and reviewed how the stakeholders rated the duration of the model calculations, and the accuracy and understandability of the modelled spatial processes. In addition, the participants filled out a questionnaire where they provided feedback on PLACES regarding its transparency and user friendliness (Pelzer, 2017).

Beyond the technological capacity of PLACES, we tested whether the stakeholders' understanding of land use effects on ecosystem services had changed before and after using PLACES at the workshop. For this, we carried out a mental model exercise, as mental models are internal representations of external reality and have been used successfully to reveal people's causal beliefs (Alomia-Hinojosa et al., 2023; Dou et al., 2023). The stakeholders were tasked to draw mental models of how they think farming practices and spatial layout aspects influence ecosystem service provision, using the application M-tool (van den Broek et al., 2021) before and after the sessions with PLACES. We provided fifteen concepts that represent the most important factors for agricultural land use of Noord-Brabant, grouped into three categories: farming practices – livestock density, manure and fertilizer application, irrigation and drainage, agricultural buildings, and the upkeep of semi-natural elements on farm sites; spatial layout – share of agriculture, share of nature, distance to agriculture, connectivity of nature, and aggregation of agriculture; and ecosystem service provision – agricultural production, water quality, air quality, habitat quality, and recreational value. The stakeholders were asked to connect these concepts with weighted arrows to indicate positive influence (arrows with weights +3, +2, +1) and negative influence (arrows with weights −1, −2, and −3).

As the number of participants ($n = 23$) precluded inferential statistics to be conducted on the mental model data, we utilized an R-script developed by the creators of M-tool to qualitatively describe changes in the mental models (van den Broek and van Boxtel, 2021). For this analysis, we calculated the number of utilized concepts and number of unique connections between concepts (i.e. arrows), as well as changes in the frequency and total weight of specific connections by comparing an aggregation of all mental models before and after the sessions. To contextualize the mental model results, we asked the stakeholders to agree or disagree with a set of statements about the driving factors of ecosystem service performance in a five-point Likert-type scale and write additional explanations to their answer before and after the sessions. We performed a deductive thematic analysis on these comments (Braun and Clarke, 2006), to assess changes in the frequency of mentioned driving factors for ecosystem services.

To assess the capacity of PLACES to facilitate a constructive dialogue about spatial planning of agriculture in mixed stakeholder groups, we gathered the stakeholders' feedback about this aspect of the tool in the questionnaire and analyzed the video-recorded discussions during the sessions. Due to the small sample size of participants, we refrained from a quantitative analysis and formal coding of the transcripts of the recordings, but instead identified common themes that emerged in multiple groups to contextualize the application of PLACES in this workshop setting.

## 3. Results

### 3.1. Utility and usability of PLACES

The review of the video-recorded sessions showed that PLACES calculated the ecosystem service consequences maps and scores within approximately 1 min. The stakeholders utilized this time mostly to further discuss their land use arrangement choices or to speculate about the outcomes. In response to the iterative interaction with the consequence maps that showed the impacts of agricultural land use on ecosystem service provision, the stakeholders formulated strategies to decrease this impact. These strategies included connecting existing nature with new natural land use or creating buffer zones of extensive agriculture around locations most sensitive to the impacts of agriculture, such as cities, water bodies, or nature. The five groups mostly achieved the requested target scores, but their final land use scenarios differed strongly in terms of the land use pattern and configuration of agriculture types and new nature.

In both the questionnaire comments and the session recordings, many stakeholders stated that they interpreted the modelled outputs as an abstract representation of reality that conveys the general principles. However, they wished for more transparency regarding the modelling approaches and the data used. Some participants experienced a lack of supplementary information: *"For me it was too much of a black box. I know the area but I just want to see a soil map."* In response, the stakeholders within a group exchanged their local knowledge during the scenario mapping. A few stakeholders expressed doubts about the representation of the agricultural land use impacts on ecosystem services due to their local expert knowledge. Some participants were interested in repeating the workshop with an adapted set of agriculture types that better reflect their experiences, such as a pig or poultry farm with high livestock density or a farm where extensive livestock and arable farming are combined. Finally, they suggested changes in the landscape canvas, including roads or city names for orientation and a differentiation of the natural land use classes into protected wetlands, forest and grasslands.

### 3.2. Increased awareness and understanding of spatial factors

In the average mental model, 13.5 (before) to 13.3 (after) out of the fifteen concepts were utilized and 18 (before) to 19.5 (after) connections were drawn. Hence, the overall complexity of the mental models remained almost the same after the sessions. However, many stakeholders restructured their mental model by creating new connections and removing others. Out of all 415 connections that were drawn in the mental models before the sessions, a large proportion (182) were exclusively present before using PLACES and were not repeated afterwards (Table 2). After using PLACES, almost half of the 449 drawn connections were newly introduced to the mental models (216) and were not present in the previous mental models.

The aggregated mental models in Fig. 2a and b shows the most important causal relationships drawn by the stakeholders before and after the sessions, while 2c summarizes the most notable changes in the stakeholders' perception. The most influential concepts before and after using PLACES were manure and fertilizer application and livestock density. Both concepts were perceived to positively affect agricultural production and negatively influence the provision of all other ecosystem services. Other concepts had overall fewer connections and were used to indicate specific influences on individual ecosystem services. For instance, semi-natural elements and connectivity of nature were mainly utilized as drivers for nature quality. Only a few connections showed the effects of ecosystem services on one another as the stakeholders were asked to primarily visualize the influence of farming practices and spatial layout. The comparison of the aggregate mental models illustrates that, after using PLACES, a specific set of connections became more relevant. Stronger positive connections were drawn from connectivity of nature and share of nature to recreation and water quality. The impacts of distance to agriculture and manure and fertilizer application on air quality became more pronounced in the stakeholders' perception. Finally, irrigation and share of agriculture were increasingly acknowledged as negative influences on nature quality, while share of agriculture remained a strong positive driver of agricultural production. A few connections became less relevant to the stakeholders after using PLACES. For instance, the effect of livestock density on air quality and of manure and fertilizer application on water quality was less acknowledged in the mental models. Overall, the farming practice concepts remained the strongest drivers of ecosystem service provision, but the effect of spatial layout got increasingly recognized after using PLACES, which is also emulated in the respective changes in the total weight of outgoing arrows from each concept (see Appendix).

**Table 2**
Distribution of connections before and after the sessions.

| | Before | After |
|---|---|---|
| Number of connections that remained the same before and after using PLACES | 233 | 233 |
| Number of connections that were exclusively present either before or after using PLACES | 182 | 216 |
| **Total connections** | 415 | 449 |

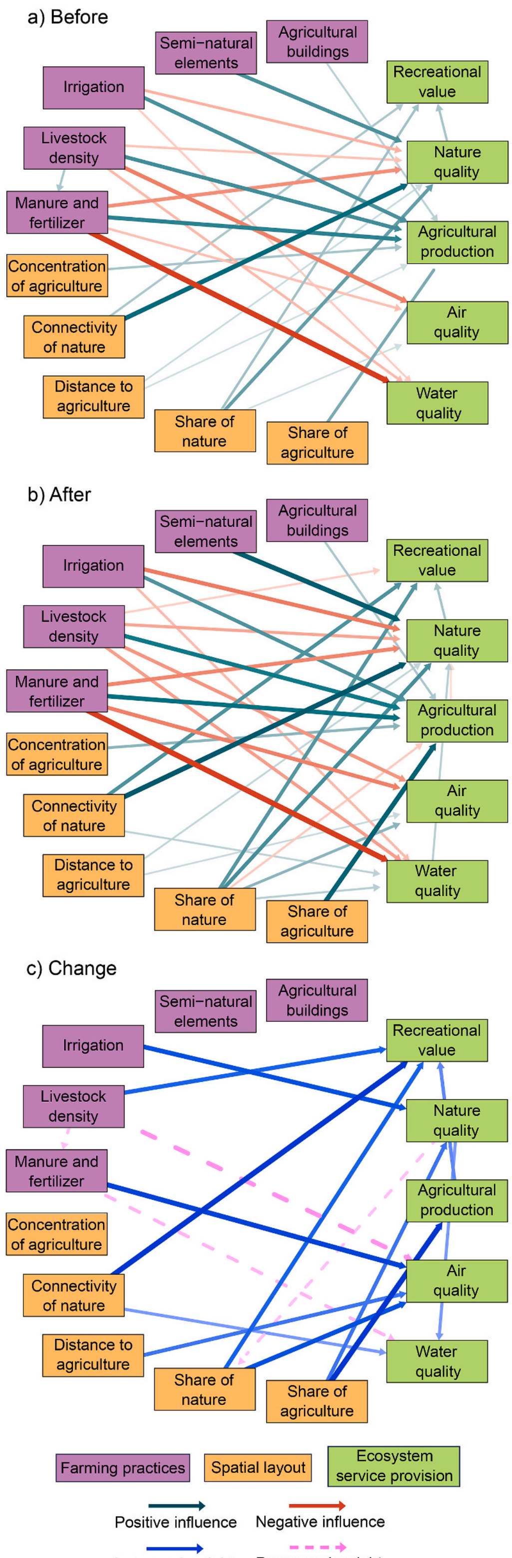


**Fig. 2a–c.** Aggregated mental models from all 23 participants (a) before and (b) after using PLACES showing the most relevant positive and negative connections. Only connections with a total weight above the absolute average weight are visualized for better readability. Darker colors refer to higher total weight of the respective connection. Changes between the aggregate mental models (c) show which connections notably increased and decreased in absolute weight after using PLACES. The connections with an absolute weight difference lower than five are excluded for better readability.

The trend towards higher priority of spatial layout effects is mirrored in the comments that the stakeholders added to their choices in the Likert-type scale statements. In these comments, the stakeholders described which local factors interact in driving ecosystem services. In comparison to other aspects like soil type, groundwater table, intensity of applied farming practices, or crop requirements, spatial arrangement aspects were acknowledged much more frequently after the sessions (Fig. 3). The list of spatial arrangement factors mentioned by the stakeholders includes corridors between nature, local concentration of agricultural practices, or distance from agriculture to vulnerable places such as nature areas and cultural landscapes.

### 3.3. Facilitated dialogue and idea exchange

In the questionnaire, the stakeholders overall agreed with statements that proclaimed that PLACES achieved to reveal the impacts of land use on ecosystem services and to start conversations about this topic. As summarized in Fig. 4, the stakeholders rated PLACES' usefulness to clarify the interactions of agricultural practices, land use arrangements and ecosystem service at an average 0.65 out of the Likert-type scale ranging from +2 (Strongly agree) to −2 (Strongly disagree). The workshop participants agreed even more clearly with PLACES' usefulness in terms of facilitating discussions on landscape planning (average Likert-type scale rating 1.23). For this statement, the ratings were also less variable and most stakeholders replied with "strongly agree".

In the additional comments to the questionnaire answers and in the debriefings of the sessions, the stakeholders described the activity as very *"fun"*, an *"eye-opener"*, and a *"conversation-starter"*. Many of them enjoyed to *"act as the scenario writer"* themselves and to be able to inspect the calculated effects of their land use arrangements immediately. With regards to the goal of PLACES to clarify the interplay of agricultural practices and ecosystem services, one stakeholder summarized that *"it is in the spatial dimension where the interaction of various forms of land use become clear."* Another participant said: *"I think people learn to argue the moment those systems become visible. […] Everything you do upstream affects you downstream."*

The workshop participants also appreciated the discussions facilitated through PLACES, which are, as one participant noted, *"an integral part of the process, where viewpoints can be exchanged and perspectives can unfold in a safe and structured manner"*. The transcripts of the video-recorded sessions of all groups revealed that the most frequent subject of discussion was the challenge of balancing multiple goals in a landscape. Initially, the stakeholders exchanged ideas on how ecosystem

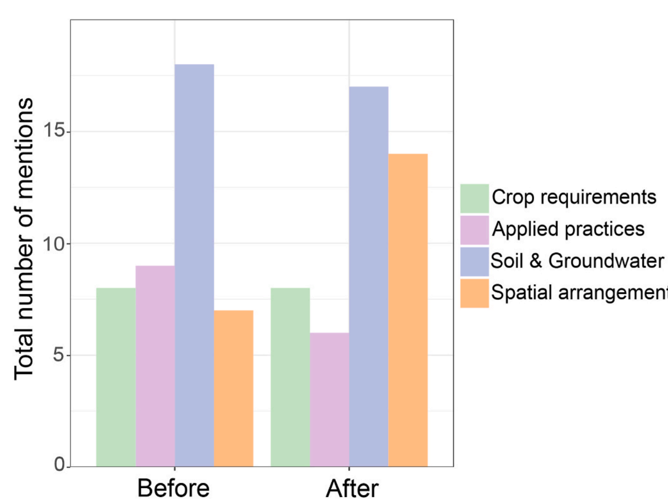


**Fig. 3.** Total number of mentions of driving factors for local ecosystem services in comments to Likert-type scale statements in the questionnaire from all 23 participants.

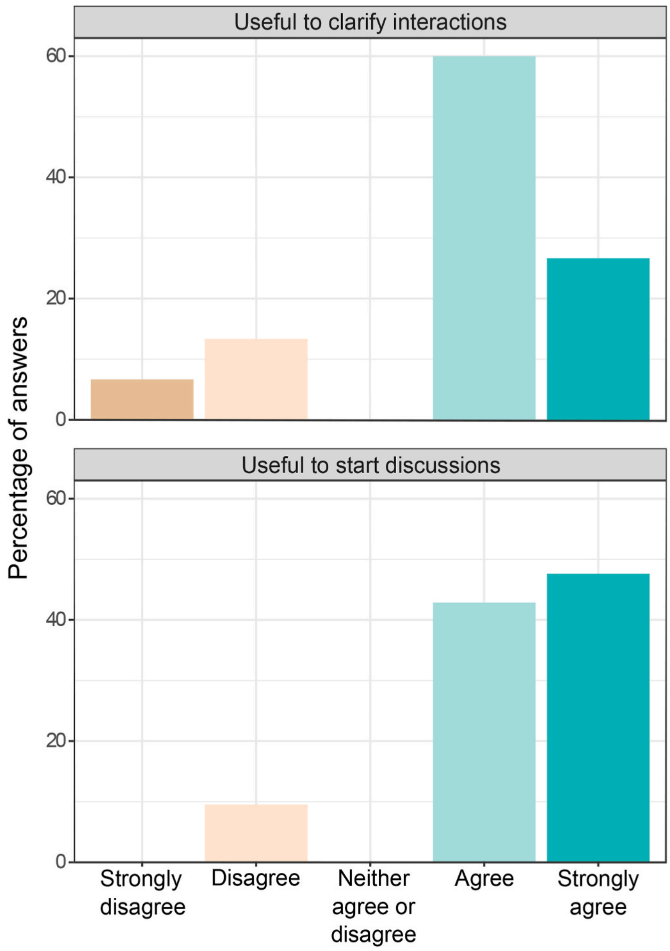


**Fig. 4.** Stakeholders' opinions on PLACES through Likert-type scale scores.

services goals should be defined and with which priority. As examples, they named goals like limited water pollution, which is part of international laws such as the European Union's Water Framework Directive, and recreation in nature, which they interpreted as a "softer" societal goal. To compare guiding principles for land use planning, the stakeholders suggested to apply PLACES with actors involved in the study area that have strongly diverging interests for ecosystem service goals. The stakeholders further discussed the different approaches to achieve these goals. Both the separation and the mix of natural and agricultural land uses were acknowledged as possible strategies. The workshop participants stated on one hand *"if we had done even more intensive agriculture in certain places, perhaps we could have achieved more nature elsewhere"*, and on the other hand *"we can use extensive agriculture instead of natural areas to make corridors"*. For the participants, the success of either strategy depended on the location and harmfulness of agricultural activities. Another topic that emerged during the discussions were the possible drivers of change in the landscape in a broader context of sustainable agriculture. The stakeholders speculated how much more space would be available to support other ecosystem services if the targets for agricultural productivity were to be adjusted to a meat-free diet or to a lower export volume of agricultural products. Subsequently, they acknowledged the role of the Netherlands for the world trade of agricultural goods: *"Where will all those countries get their food from if we extensify?"*.

## 4. Discussion

### 4.1. Evaluation of tool design and application choices

According to the results of our stakeholder workshop, PLACES was capable of producing outputs that were relevant, credible, and understandable to participants with mixed background knowledge, which is a guiding design principle of tools that bridge science and policy (Cash et al., 2003; van Hardeveld et al., 2019). In contrast to existing tools (Metzger et al., 2021), PLACES simulates landscape-level processes and visualizes spatially-explicit land use impacts on ecosystem services comprehensively. This design enabled the workshop participants to use the tool outputs to strategically adjust their land use scenarios and ultimately achieve the conflicting ecosystem service targets. Moreover, the short calculation times enabled the flow of conversation around the simulated land use effects. From the workshop results, we conclude that the level of detail with which the consequences of land use on ecosystem services are simulated was correct for the purpose of the application and for the present audience. During the model development, we elicited expert knowledge to create fast and reality-based models. However, the challenge to balance simplicity and realism in the models became very apparent during the application of PLACES, as some stakeholders indicated that the model outcomes deviated from their experience. On one hand, increasing the realism in the models could increase the understanding and trust in the models (Walling and Vaneeckhaute, 2020). On the other hand, simplified models are accessible to more stakeholders (Ruckelshaus et al., 2015) and enable a faster runtime that is essential for stakeholder interaction (van Hardeveld et al., 2019). To increase the credibility of the model outcomes, experts from different fields should be involved in customizing the scope of the models and in challenging its assumptions (Merritt et al., 2017). These expert consultations can be expanded into participatory modelling processes depending on the knowledge of the target user audience (Walling and Vaneeckhaute, 2020; Zellner et al., 2022).

The importance of transparency regarding the input data and calculations performed by a given tool is highlighted by several studies, specifically for high-stakes decisions (Walling and Vaneeckhaute, 2020). As the purpose of our workshop was to increase system understanding and enable communication among stakeholders and not to support decision-making in a real case, we chose to provide simplified illustrations of the processes simulated in PLACES instead of explaining the specific modelling approaches. This choice was made to promote the conversation flow and to focus the participants' attention on the core phenomena. However, several stakeholders wished for more information on the functionality of the models or the underlying data. To improve the credibility of the model outputs, specifically for well-informed participants, the approaches and assumptions within the models should be communicated much more transparently in future applications (Jakeman et al., 2011). This would also enhance the user's trust in the model outcomes (Hewitt and Macleod, 2017). Tailored to the specific audience, a more detailed graphical representation of the used data and applied calculations could be provided. The level of detail of this material has to be carefully chosen to not impose undue pressure on the participants to make the right decision (Zellner et al., 2022).

The user friendliness of a tool interface is another relevant factor for a successful tool (McIntosh et al., 2011). For PLACES, the user friendliness was strongly linked to the landscape canvas in the front end. Consequently, a major point of discussion during the customization of PLACES for the stakeholder workshop was whether a fictional landscape or the actual case study area should be presented as the canvas. A fictional landscape may be more useful to conceptually visualize specific processes, which can be utilized to broadening people's beliefs and knowledge (Mckenzie et al., 2014). Yet, stakeholders might be less engaged when working with a fictional landscape. At our stakeholder workshop, the simplified representation of a real and familiar landscape motivated the participants to implement their goals for the landscape and contributed to the communication among them. Yet, we observed that at times the stakeholders' local knowledge and own interests interfered with the process. Hence, for future applications of PLACES, the choice for a real or fictional landscape should be carefully contemplated based on the specific context and purpose. The prospective users can be engaged in the landscape canvas design to increase the relevance and credibility of the overall application (Merritt et al., 2017).

### *4.2. Facilitation of system understanding and discussions*

The detected changes in the mental models and in the questionnaire comments demonstrated that PLACES increased the participants' insights into the system at hand, specifically regarding the role of spatial processes for ecosystem service provision (Figs. 2 and 3). It is most likely that the spatially-explicit visualization of agricultural land use impacts on ecosystem services in maps brought landscape configuration effects to the attention of the stakeholders. For instance, our modelled output for air pollution in cities highlighted the distance-decay of particulate matter emissions from agricultural land, enabling the stakeholders to trace the origin of the impact. This is supported by the observation that distance to agriculture was used more often as a driver of air quality in the mental maps after using PLACES. Further, PLACES simulated habitat isolation and loss of recreational value based on the amount and spatial context of beneficial and non-beneficial land uses. Concurrently, the share of nature and connectivity of nature were increasingly recognized as positive influences on recreational value and nature quality in the mental models. The interaction with the maps during the workshop possibly also enhanced the stakeholders' spatial thinking and grasp of spatial concepts (Metoyer et al., 2015), leading to a stronger inclusion of these concepts in the mental models. In the questionnaire answers, the stakeholders also acknowledged the complexity of ecosystem service provision at landscape level, specifically with the frequent mention of "distance to vulnerable places", which describes both spatial configuration and sensitivity of a given land use to environmental damage. In future applications of PLACES, the tool's contribution to increased understanding of spatial arrangement effects should be evaluated in greater detail, for instance by measuring the participants' ability and motivation to draw complex mental models (Haug et al., 2011) and their activity level during the participatory sessions (Baird et al., 2014).

According to the stakeholders' feedback in the questionnaire and in the video recordings, the workshop with PLACES facilitated discussions on the transition to sustainable agriculture, covering three main themes: 1) the inevitability of having to make trade-offs in ecosystem service delivery when facilitating the goals of various stakeholder groups for different landscape functions; 2) the processes required to implement changes for a more sustainable rural landscape; 3) the broader and more fundamental changes necessary to get to a sustainable agricultural system. It is important to note that for most of the stakeholders, the added value of applying PLACES was that perspectives and visions on these themes could be exchanged in a sociable setting. Hence, stakeholder workshops with tools that provide feedback on the participants' landscape designs can possibly provide settings where stakeholders with strongly divergent opinions and interests can cooperate. As confirmed by participatory approaches in other European countries, incorporating multiple goals and discussing their ecological, social, and economic values contributes to the formation of a shared vision for the landscape (Dick et al., 2017; Lopes and Videira, 2018; Malmborg et al., 2022; van Hardeveld et al., 2018). Tools like PLACES could be applied in various settings as a mediator between stakeholder groups, as they can bring new arguments into the debate and allow for multiple land use scenarios to achieve the ecosystem service goals. Debating the consequences of different land use arrangements can further operationalize concepts like land sparing and land sharing for the regional context (Karner et al., 2019), thereby facilitating reflection on different directions, and more fundamental choices, for making our food system more sustainable (Springmann et al., 2018).

## 5. Conclusion

The application of PLACES demonstrated that simulation tools for land use effects on ecosystem services benefit greatly from modelling simplified landscape-level processes. The tool users can gain a deeper understanding of the driving factors for ecosystem services supply in a landscape and utilize it interactively to balance out ecosystem service tradeoffs. Fast result compilations prompt users to identify the reasons for the encountered effects and enable them to critically discuss and redesign their landscape scenarios. Through the interaction with ecosystem services consequence maps, a debate can emerge concerning the guiding principles for land use planning as well as options and drivers for a spatial reorganization of the landscape. For further adaptations of PLACES or similar tools, we identify three aspects for successful support of participatory spatial planning debates. First, comprehensive and spatially-explicit representation of land use effects on ecosystem services should be used to spark awareness of spatial processes in participatory approaches. Second, to bridge the gap between science and policy, the understanding of ecosystem service provision and tradeoffs should be supported by clarifying the interaction of underlying drivers. This applies still when the stakeholders involved are very familiar with the spatial planning conflicts at hand. Third, we recommend to tailor models of land use effects on ecosystem services and the visualization of landscapes to the knowledge and expectations of the target audience to improve the applicability of participatory planning tools to a wide range of stakeholders.

## Software and data availability

Software available at:
https://github.com/s-gebhardt/places

## CRediT authorship contribution statement

**Swantje Gebhardt:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia C. Assis:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization. **Martin Lacayo-Emery:** Software, Resources, Methodology, Conceptualization. **Addowa Scherpenisse:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karlijn van den Broek:** Writing – review & editing, Resources, Methodology, Formal analysis. **Erika Speelman:** Writing – review & editing, Resources, Methodology. **Martin J. Wassen:** Writing – review & editing, Supervision, Conceptualization. **Martha Bakker:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jerry van Dijk:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

## 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. Supplementary data

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