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Optimizing the allocation of agri-environment measures to navigate the trade-offs between ecosystem services, biodiversity and agricultural production

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ABSTRACT

Demands on peri-urban landscapes are increasing and diversifying. These landscapes typically fulfil different functions, including agriculture, ecosystem services and may also host species and habitats of conservation concern. Designing landscapes that can simultaneously meet multiple competing demands is an important challenge. Addressing this challenge requires methods that can provide a clear understanding of the trade-offs between biodiversity, production and ecosystem services, and that can assist in effectively navigating these through planning. Here, we tested the degree to which landscape optimization algorithms can do so, for an intensively-used area in the Netherlands. We optimized land use/land management to increase fruit yield, endangered species habitat, and landscape aesthetics, while minimizing losses in dairy farming, and assessed the trade-offs among these objectives. We considered the allocation of on-farm measures (organic management and establishment of linear elements), off-farm measures (taking land out of production) and a combination of both. Both agri-environment measures were able to contribute to the objectives but showed strong trade-offs between fruit yield (on-farm: +26.19% vs. off-farm: +1.63%) and species habitat (on-farm: +9.90% vs. off-farm: +45.72%). Using a combination of both on-farm and off-farm measures largely alleviated this trade-off. The spatial allocation of measures in the landscape was important, and priority areas according to our optimization technique differed markedly from those in the existing nature conservation plan, which is primarily focused on species conservation. Our results highlight that the current nature conservation plan can be improved, thereby simultaneously contributing to multiple environmental objectives while incurring a smaller impact on dairy farming. Comparing *on-farm* and *off-farm* management practices provides insight in the functional trade-offs associated with each management option and their respective potential to increase multifunctionality. Moreover, the identification of priority locations across all solutions can further integrate landscape optimization approaches into spatial planning and inform policy design and implementation.

1. Introduction

Human demands on landscapes are multifold and these demands often compete for the same space. Agricultural landscapes have often been optimized for the production of food, resulting in declines of both biodiversity and non-provisioning ecosystem services (Bennett et al., 2009; Seppelt et al., 2016). However, with increasing human population size and peri-urban development the multitude of demands on these landscapes often increases (Zasada et al., 2013). To meet multiple demands in the future, many studies suggest that agricultural landscapes should become multifunctional (e.g. O'Farrell and Anderson, 2010; Fischer, et al. 2017b). A shift towards a more multifunctional landscape may require changes in farm management and nature restoration (Tscharntke et al., 2012, 2005). However, such shifts inevitably involve trade-offs between conflicting objectives (Fischer et al., 2017a,b; Howe et al., 2014). Understanding and balancing these trade-offs therefore has a high priority on the policy agenda. Current trade-off research needs to move beyond the identification of trade-offs towards the development of tools that can assist landscape planners in effectively navigating these trade-offs, e.g. by supporting target setting

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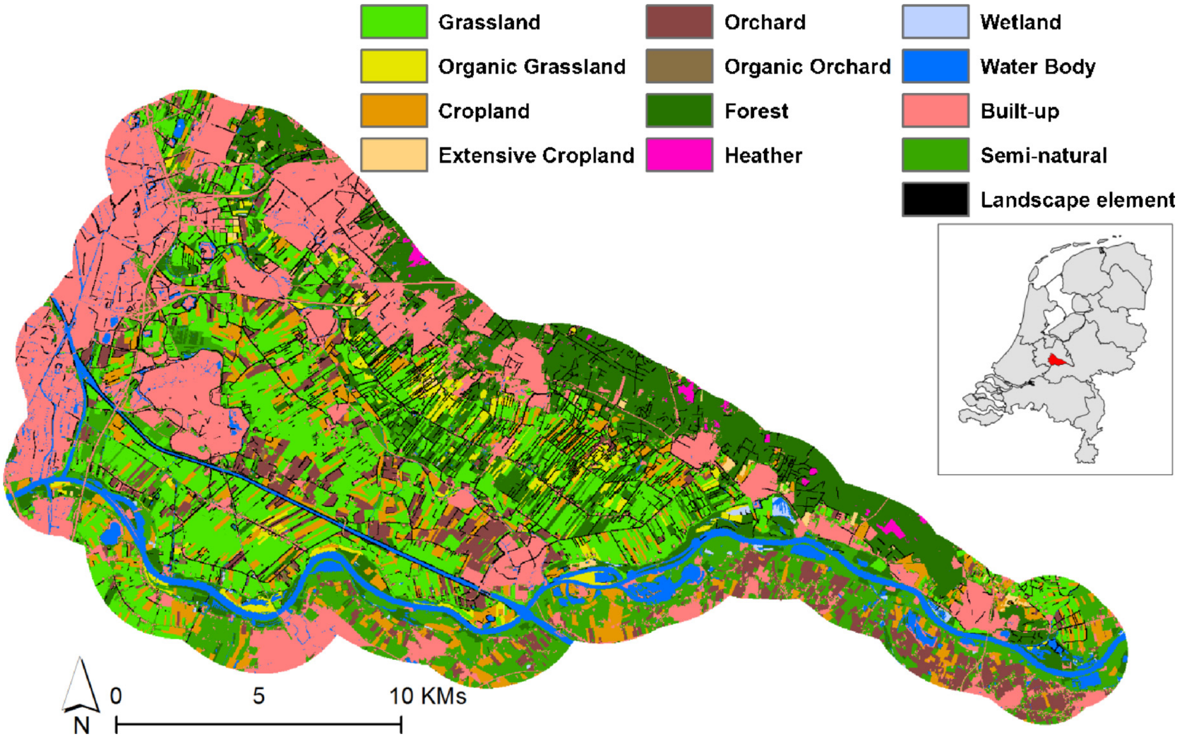

Fig. 1. Land use land management map of the study area depicting the main agricultural land systems. The inset of the map shows the location of the Kromme Rijn area (in red) within The Netherlands. The land system map is depicted with a 2 km buffer. The number of classes (41) in the actual map is simplified for visualization purposes (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

based on alternative 'optimal' management strategies (Bennett et al., 2015; Seppelt et al., 2013; Verburg et al., 2016).

In the presence of such trade-offs, optimization algorithms are capable of identifying a set of Pareto-optimal land use and land management (LULM) configurations (Gourevitch et al., 2016; Kennedy et al., 2016; Lautenbach et al., 2013; Nelson et al., 2009; Pennington et al., 2017). Previous analyses have shown that trade-offs not only exist between agricultural production and regulating ecosystem services, but also between individual ecosystem services themselves (Gourevitch et al., 2016; Howe et al., 2014; Kennedy et al., 2016; Nelson et al., 2009). Optimization algorithms can provide insight into the functional trade-offs between two or more objectives and provide a full set of possible future LULM allocations (Cord et al., 2017; Lautenbach et al., 2013; Seppelt et al., 2013). Optimization algorithms can therefore depict the effects of landscape management options for multiple objectives simultaneously, and provide alternative pathways for balancing these trade-offs (Cord et al., 2017; Seppelt et al., 2013; Verburg et al., 2016). Furthermore, optimization approaches hold great potential for bridging the science-policy divide by comparing current conservation plans and alternative scenarios to the full set of alternative future LULM allocations (Cord et al., 2017; Seppelt et al., 2013).

A landscape's multifunctionality can be increased using a diverse set of LULM options such as restoration of natural areas or changes in farm practices (Batáry et al., 2015; Seppelt et al., 2016; Duru et al., 2015; Lovell and Johnston, 2009). In addition, green linear elements, such as hedges and tree lines, are capable of providing multiple ecosystem services and hold great potential for landscape optimization in agricultural areas (Jones et al., 2013; Kremen and M'Gonigle, 2015; Verhagen et al., 2016). Policy instruments to increase the multifunctionality in European landscapes also cover this full range, from policies mostly focused on changes in farming practices through the EU Common Agricultural Policy (rural development and agri-environment measures) to policies focussed on restoration of green infrastructure.

Previous landscape optimization analyses have either focused on restoration of natural areas (*off-farm*) (Gourevitch et al., 2016; Kennedy et al., 2016; Nelson et al., 2009) or on allocating a set of farm management alternatives (*on-farm*) (Lautenbach et al., 2013; Pennington et al., 2017). Previous research further showed the potential of optimization algorithms in minimizing trade-offs between forestry, biodiversity and ecosystem services, following forest restoration in Uganda (Gourevitch et al., 2016) or optimizing crop rotations schemes for food production, biofuel crops and river management (Lautenbach et al., 2013). However, *on-farm* and *off-farm* management practices have hardly been compared nor combined in landscape optimization analyses limiting our knowledge on the functional trade-offs associated with each management option and their respective potential to increase multifunctionality.

This paper presents a multi-objective landscape optimization for *on-farm* and *off-farm* agri-environment measures for the Kromme Rijn area, The Netherlands. The Kromme Rijn area is an agricultural landscape dominated by pasture production, rich in green linear elements. We compare landscape optimization for *on-farm* and *off-farm* agro-environment measures for indicators of production, biodiversity and ecosystem services. We compare our outcomes to the current nature conservation plan to assess possible improvements of that plan with respect to the values per objective and the priority locations for agri-environment measures.

2. Methods

The method section consists of four parts. We first provide the background of the study area and the current nature management. We then describe the spatial data used in this study. Third, we present the models used to quantify the environmental objectives and fourth, we describe the optimization method.

2.1. Case study background

2.1.1. Case study area

The Kromme Rijn area (Fig. 1) is a peri-urban agricultural