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 fulfill 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.
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
dominated landscape of \( \sim 219 \text{ km}^2 \), located in the Province of Utrecht, The Netherlands (52°06′28.1″N - 51°57′17.6″N; 5°06′10.3″E - 5°37′10.2″E) (OKRA Provincie Utrecht, 2011). The landscape is characterized by an old tributary of the river Rhine, the Kromme Rijn, meandering through the area. The agricultural landscape in the area is rich in woody linear elements and characterized by a NW-SE gradient in openness. In the northern section, the banks of the Kromme Rijn are flanked by estates dating back to the 19th century. Pasture production around these estates is intertwined with remnants of natural vegetation and bordered in the north by forests. In the rest of the area the main agricultural activity is dairy farming combined with fruit production on sandy and clay levee deposits of the former riverbed. In addition to its agricultural function, the area has high aesthetic quality and is an important recreational area for the city of Utrecht (Geerdes et al., 2016; Utrecht Province, 2017).

A nature conservation plan (NCP) was developed by the province to enhance species conservation in the Kromme Rijn area. The NCP focuses on the restoration of habitat for a set of focal species, including the great crested newt, the common noctule or the long eared owl (Utrecht Province, 2017). In the NCP, agricultural land is assigned to be taken out of production and typically restored towards natural grassland. In addition, the NCP promotes the establishment of green linear elements, such as hedges and tree lines, on agricultural land. Establishment of these elements is a voluntary measure but is eligible for financial support. A set of stakeholder workshops (March 2016 and December 2016) revealed that farmers consider the transition to organic farming as an important alternative to conventional farming, given recent high prices for organic milk. The transition to organic management is not considered in the NCP and is not eligible for financial support. The NCP does not consider additional environmental objectives important for the Kromme Rijn area, such as its aesthetic landscape value or fruit production. Especially of interest are the traditional/extensive orchards, which support biodiversity and ecosystem services besides providing fruits.

2.2. Spatial information

2.2.1. Land use and land management map

We made a land use land management (LULM) map at 25 × 25 m resolution based on a combination of land cover, crop types, management intensity and the location of linear elements, yielding 41 different land use types (Supporting information). All agricultural areas were assigned a combination of land management and presence of linear elements, resulting in four categories: conventional without linear elements, conventional with linear elements, organic without linear elements and organic with linear elements.

For the delineation of organic and conventional management for orchard and pasture fields, we developed a map of organic agriculture based on the addresses of all organic farms, which we obtained from the control agency of organic farming (SKAL, 2017). We assigned organic management to crop fields based on the location of organic farms, their main crop production type, average farm size per production type and a spatial data set of crop types per field (see Supporting information). Fields closest to an organic farm were assigned organic management until the area of the fields equalled the average farm size. Within a field, all cells were either under conventional or organic management. Information on the management of natural areas was obtained from the most recent nature conservation plan (NCP; Utrecht Province, 2017).

In addition, we identified the presence of linear elements in cells, using a detailed dataset on the location of tree lines and hedges (Utrecht Province, 2013). The extent of linear elements is commonly smaller than the resolution used to map dominant LULM types per cell. Therefore, we determined for each cell whether linear elements were present and subsequently categorised each LULM into two categories; with or without these elements. A detailed methodology behind making the LULM map and a list of all LULM types is provided in the supporting information.

2.3. Environmental objectives

We modelled three environmental objectives, namely fruit yield, aesthetic landscape value and habitat suitability for great crested newt (Triturus cristatus). As the implementation of agri-environment measures comes at a cost of pasture production, we quantified the loss in pasture production, whose minimization served as a fourth objective. The four objectives were selected based on relevance to the study area using input from stakeholder workshop, the nature conservation plan and other reports (Geerdes et al., 2016; Utrecht Province, 2017). Also, they represented different types of objectives for landscape planners, namely agricultural production, a cultural ecosystem service and a biodiversity indicator. The models used to quantify each objective are described in full in the supporting information. Below we describe the main characteristics. All the environmental models were written in R (Core Team, 2016).

2.3.1. Pasture production for dairy cows

The model of pasture production for dairy cows (euro/ha/year) was based on a look-up table approach. We calculated the profit per cell based on average production values per ha pasture, the costs of milk production and market milk prices for the Netherlands (agrimatie.nl, 2014). All data were averaged over the years 2010–2014. We used animal feed as the cost measure, since it is an important cost in switching from conventional to organic farming (SKAL, 2017).

We accounted for pasture management by using different production quantities, market prices and costs for organic and conventional pastures. We also accounted for a transition period of six months for farmers switching to organic management. During this transition period farmers already implemented organic management on the field, which leads to lower production outputs and higher costs, but the products are still sold for conventional market prices (SKAL, 2017).

The presence of linear elements lowered the amount of land in production per cell. In all models we used hedges to approximate the effects of linear elements, with a standard width of 5 m. This width is within estimates of previous studies using hedgerow widths varying between 3–10 meter (Van Teeffelen et al., 2015; Schulp et al., 2014).

We calculated the total profits of pasture production per cell for a period of ten years to be able to include transition costs to organic farming. Given the current price-cost ratio, conventional management is most profitable and therefore both a transition to organic farming or restoring linear elements incurred a financial loss. We therefore assumed a reduction in pasture production as an opportunity cost of foregone production. To estimate this opportunity cost, we first calculated the maximum pasture production, i.e. the pasture production if all pastures were assigned to conventional management without linear elements. Costs of foregone production were then calculated as the pasture production with the newly assigned LULM allocation minus the potential pasture production.

2.3.2. Fruit yield

Fruit yield (euro/ha/year) was modelled based on the level of pollination per orchard coupled with a look-up table approach to quantify the costs and benefits. Fruit tree production partly depends on pollination for fruit set. Pollination by wild bees and other pollinators is more effective and more resilient against diseases than pollination by domesticated honeybees (Garibaldi et al., 2013; Potts et al., 2010). We therefore adopted an existing pollination model by Zulian et al. (2013), linking the landscape suitability for wild bees, based on nest suitability, floral resources and distance to orchards. In a second step, we calculated the fruit yield based on estimates of production, costs and market prices for apples and pears, which are the most dominant fruit crops in the Kromme Rijn area (Supporting information).

In our model, bee habitat quality and pollination potential increased
by either: the presence of hedges, a transition to organic farming or by taking pastures out of production. Agri-environment measures in orchards and on pastures nearby orchards also increased the pollination potential within orchards.

We used a look-up table approach to quantify the profits of fruit yield per cell. We obtained production estimates, costs and market prices for organic and conventional orchards producing apples and pears (de Groot et al., 2016, 2015; Heijerman-Peppelman and Roelofs, 2010). Again we used a transition period to account for the costs associated with switching to organic farming. The transition period for fruit yield is three years (SKAL, 2017).

We calculated the total fruit yield over a period of ten years. Given that the current market prices of organic fruit tree production are high, the costs endured in the first three years are outweighed by the additional profits in the later years.

2.3.3. Aesthetic quality

We quantified the aesthetic quality of the landscape using a model specifically designed for the Kromme Rijn area (Tieskens et al., under review). The model linked the amount of unique user uploads of landscape photos on social media platforms to the location of a set of structural landscape features (Panoramia and Flickr). Most spatial predictors in the model were relatively fixed, including the location of forts, rivers, castles, walking and bicycling tracks as well as population density. For the natural landscape features, the distance to both natural grasslands as well as linear elements had a significant impact on the amount of unique user uploads (Tieskens et al., under review). Therefore these type of agri-environment measures improved the aesthetic quality. Pastures and orchards did not affect aesthetic quality, irrespective of the management type (Supporting information).

2.3.4. Great crested newt occurrence

The Kromme Rijn area is a focal area for the protection and restoration of habitat for the great crested newt (Utrecht Province, 2017). The nature conservation plan specifically mentioned the need to manage the land for this particular species in our study area (Utrecht Province, 2017). As a biodiversity indicator, we therefore opted for a model on the habitat suitability (number of individuals/pond) for the great crested newt within our optimization approach (Van Teeffelen et al., 2015). We calculated the carrying capacity for great crested newt for individual ponds as a function of the location of ponds and the amount of suitable habitat in the vicinity of the pond (Van Teeffelen et al., 2015). The newt model by Van Teeffelen et al. (2015) was developed and applied in the Bankse Beek, a Dutch agricultural landscape dominated by dairy farming. Ponds are considered important for newts, as they require ponds for reproduction. The landscape surrounding a pond is used for feeding, shelter and hibernation in the juvenile and adult stages (Griffiths, 1996; Müllner, 2001).

In our model, the amount of individuals each pond can support depended on the habitat suitability of the surrounding landscape. Habitat suitability was a function of the amount of forested habitat, natural grassland and hedgerows within the surroundings of a pond (Van Teeffelen et al., 2015). Pastures and orchards were not suitable habitat irrespective of their management. We obtained the location of ponds (Utrecht Province, 2017) and calculated the potential number of individuals per pond based on the habitat suitability of the LULM surrounding the pond (250 m radius) (Van Teeffelen et al., 2015).

2.4. Landscape optimization algorithm

2.4.1. Objective functions

We used a multi-objective optimization algorithm to optimize the allocation of LULM in the Kromme Rijn area. Our goal was to simultaneously:

1. maximize yearly fruit yield profit in euro/year on the land currently under production - calculated for a ten year period, summed for all orchard cells in the area;
2. maximize potential newt habitat - measured as newt individuals per pond, summed for all cells containing ponds in the area;
3. maximize landscape aesthetics - measured as the number of unique user uploads of landscape photos to social media platforms, summed for all cells containing hike or bike paths;
4. minimize the loss in pasture production - measured as euro/year for a ten year period, summed for all pasture cells in the area.

2.4.2. Optimization algorithm

Optimization in this approach resulted in the increase in the objective functions following changes in LULM applied to pastures and orchards. We used a recently developed landscape optimization tool Constrained Multi-objective Optimization of Land-use Allocation “CoMOLA” (Strauch, 2018), a Python environment that can be linked to user-specific models. CoMOLA utilizes the non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002) and allows to consider land use change constraints.

Based on the original LULM map (starting solution) and pre-defined constraints (land use transition and area proportion rules) the genetic algorithm first created a set of different yet feasible LULM allocation maps. This set is called a population. Each map is called an individual and is encoded as a string of integers, a so-called genome. Using the environmental models described above, each individual was assigned fitness values representing the achieved values for the four objectives. The algorithm then applied a Pareto ranking for each individual based on its fitness values, archives best individuals and selects individuals for mating to generate a new (offspring) population. In mating, each offspring individual was generated by a random combination (crossover) of two genomes. The likelihood of mating increased for individuals with a higher rank. Additional random mutations increased the diversity of genomes to consider a wide range of LULM allocations. Mating can result into infeasible, i.e. constraint-violating, offspring individuals. The genomes of infeasible individuals were modified using a repair mechanism specifically developed for land allocation optimization. The whole procedure from fitness value calculation to offspring generation and genome repairing was repeated until a termination criteria is reached, e.g. a convergence criteria or a pre-defined number of generations. In this manner the algorithm approaches towards the Pareto-front, which allocates LULM in a way that no increase of one objective was possible without decreasing another. The Pareto-front thus defined the optimal trade-off between the objectives. Although no optimization algorithm can guarantee to find optimal solutions, genetic algorithms are known to find at least close to optimum solutions (Lautenbach et al., 2013).

2.4.3. Allocation of agri-environment measures

To maximize the objective functions, we allocated different LULM to pastures and orchards. Pastures and orchards could be assigned a total of four LULM based on a combination of farm management (conventional and organic) and establishment of linear elements (on-farm measures). In addition, pastures can be taken out of production (off-farm measure). As pasture production areas are most commonly restored to natural grasslands, we used values for natural grassland to calculate the effect of pastures taken out production on objective functions. Orchards could not be taken out of production.

Farmers were the primary decision makers to assign LULM to pastures and orchards. Due to computational limitations, in our approach it was only possible to allocate LULM to aggregated decision units. Given our focus on farmers, we used farms as decision units. We allocated individual cells to farms based on crop type, delineation of fields (CBS, 2014) and the location of dairy and fruit orchards (Utrecht Province, 2011) (see Supporting information). The Kromme Rijn area included a total of 277 pasture farms and 141 fruit orchards. In our aggregation routine, all cells in a farm were assigned a single LULM type. The
decision to implement organic or conventional management is often taken at the farm level given the need to fully separate production cycles (SKAL, 2017).

The establishment of linear elements can differ both between and within fields. However, the optimization algorithm only allowed allocation of elements to all cells in the farm, given computational limitations that do not allow for allocation of elements to individual cells. In the calculation of each objective we accounted for the difference between field interior and field edge. Linear elements were assigned to the full farm. However in a second step we combined the map of linear elements at the farm level with a binary map of field edges and field interiors at the cell level. Thus linear elements were only allocated on field edges within farms that adopted linear elements as farm management technique (see Supporting information).

Optimizing the allocation of LULM started from a starting solution, usually the original LULM map. However, due to computational limitations we simplified the original LULM map for its use as starting solution in a way that only a single LULM is assigned to each farm. Given that farm management is assigned on farm level and linear elements differ within farms, we generated a starting solution without linear elements. For the starting solution, we only assigned the LULM conventional or organic management without linear elements to each farm. In the LULM optimization linear elements could be assigned at the farm level.

2.4.4. Agri-environment experiments

We ran a total of three optimization experiments, differing in the type of agri-environment measures implemented: 1) on-farm: pastures and orchards can only be assigned a change in farm management and/or establishment of linear elements. This experiment quantified the optimal trade-off for agri-environment measures only focused on changing farm practices, 2) off-farm: pastures can only be taken out of production, with no change in orchards. This experiment quantified the optimal trade-off if agri-environment measures would only focus on taking land out of production. 3) all options: pastures and orchards can be assigned to all LULM categories, combining on-farm and off-farm agri-environment measures. This experiment quantified the Pareto-optimal trade-off if all LULM options could be combined. Across all experiments the LULM allocation was performed for 277 pasture farms and 141 fruit orchards.

In addition to the LULM transition rules defined for each experiment, we limited the extent of change in allocation of LULM per category as a further optimization constraint. For pastures, we calculated the amount of land taken out of production proposed in the conservation plan and limited the amount of change from conventional management to another LULM allocation by this. Therewith we limited the loss in pasture production by the expected loss incurred in the nature conservation plan. We used yearly transition rates of conventional to organic orchards to calculate the allowed change from conventional orchards to orchards with agri-environment measures (see Supporting information).

Last, for each experiment we used a population size of 100 LULM allocations (individuals) and ran a total of 100 generations. We repeated each experiment ten times. For each experiment we thus generated a total of 10,000 LULM allocations for comparison in each repetition.

2.4.5. Analysis of results

Each landscape optimization experiment resulted in a set of non-dominated LULM allocations. For each land allocation we calculated a set of indicators. First, we visualised the functional trade-offs between objectives by calculating the percentage change for a LULM allocation per objective relative to the value of that objective for the starting solution. The starting solution was a simplified version of the current landscape without linear elements assigned at the farm level.

Second, any multi-objective landscape optimization will generate a diverse set of optimal outcomes. A challenge lies in translating a large set of non-dominated outcomes to targeted spatial planning advice. We adopted an approach by Karakostas (2017) and calculated the relative frequency a cell was assigned to agri-environment measures across all LULM allocations per experiment. This approach identified locations that (almost) always have agri-environment measures irrespective of their location at the Pareto-front.

Last, we compared the outcomes of the optimization analysis to the current landscape and the proposed conservation plan. For each LULM allocation we calculated the relative change compared to the current landscape, containing linear elements and varied LULM at the cell level. This analysis provides insight into the extent that the current landscape and the nature conservation plan can be improved with different LULM allocations.

We performed ten runs for each scenario. For each run, we calculated the hypervolume of the Pareto-front as a performance measure indicating the volume of the dominated portion of the objective space (Jiang et al., 2014; Zitzler and Thiele, 1999) (Supporting information). For each scenario we selected the run with the best performance, i.e. highest hypervolume value at the end of the run. The similarity in the hypervolume curves among repetitions indicates an overall robustness of our results. All analyses were performed for the non-dominated solutions for that run. All analyses were performed using R (Core Team, 2016).

3. Results

3.1. Functional trade-offs per agri-environment measure

All agri-environment experiments increased the environmental objectives at the cost of pasture production (Fig. 2). We visualized the four-dimensional Pareto-front for the all options experiment (Fig. 2, top Panel). In addition we visualized the trade-off between pasture production and each environmental objective for all options (Fig. 2A), off-farm measures (Fig. 2B) and on-farm measures (Fig. 2C). The extent to which each environmental objective is enhanced differed strongly per experiment. Focusing solely on on-farm measures, these strongly enhanced fruit yield (max 26.19% increase), calculated as the change in fruit yield relative to the starting solution, but had a smaller (positive) impact on newt habitat (max 9.90% increase) (Fig. 2C). In contrast, focusing on off-farm measures had a strong positive impact on newt habitat (max 45.72%), but hardly enhanced fruit yield (+ 1.63%) (Fig. 2B). Aesthetics was most strongly affected by off-farm measures, but the effect of all measures was relatively small. The limited gains of different LULM for landscape aesthetics was due to the fact that aesthetics is affected by many fixed factors, such as distance to castles, water and forest.

In general, decreasing pasture production resulted in increases for all other objectives. However, a 26.2% increase in fruit yield can also be achieved without losses in pasture production (Fig. 2C). These strong initial gains were achieved by on-farm measures on orchards. Increases in the other objectives can only be achieved with decreasing pasture production and thus always result in a trade-off.

Agri-environment measures including all LULM allocations, all options, was capable of simultaneously enhancing newt habitat and fruit yield (Fig. 2A). While the maximum values for fruit yield (+ 25.57%) and newt habitat (+ 44.72%) were slightly higher than the maximum values that could be achieved in the other experiments, these differences are very small. Overall, these results showed that all agri-environment alternatives considered can increase the landscape’s capacity for these three environmental objectives simultaneously, demonstrating how the current landscape can be enhanced. Having said that, the strength of the trade-offs among objectives changed with different sets of agri-environment measures available, indicating that careful target-setting is important.
3.2. Spatial priorities for agri-environment measures

We identified spatial priorities for LULM allocations (Fig. 3). We only visualised the results for the all options experiment, because this experiment has the highest potential for creating synergies among objectives. In this experiment, only a few areas were assigned an agri-environment measure across all optimal LULM allocations (Fig. 3A). These areas were mainly located in and around orchards in the centre of the Kromme Rijn. This showed a mismatch with the areas designated in the nature conservation plan, as these are mostly at the edge of the Kromme Rijn area, for example around rivers and existing nature areas (Fig. 3D). The conservation plan is solely developed for species protection, but does address more species than just the newt, partly explaining the difference in locations. Our results indicate that if additional objectives and agri-environment measures would be included in the conservation plan, the preferred locations for these measures would be located differently. Mainly, preferred locations would move to the centre of the Kromme Rijn area in and around orchards.

Fig. 2. Pareto-optimal land use land management allocations per agri-environment experiment. Each point represents a single Pareto-optimal solution. The top figure represents the 4-dimensional trade-off curve for the “all options” experiment (A). The bottom nine panels represent the trade-off between pasture production and each environmental objective for (A) all options, (B) off-farm measures and (C) on-farm measures. Pasture production can decrease by more than 100% because it is quantified as an opportunity cost (i.e. a loss) and not as the actual profit from pasture production. The interested reader can also find a 3-d visualization of the Pareto-frontier for each scenario in the supporting information.
The frequency with which a cell is assigned to an agri-environment measure does not indicate the type assigned to that cell. Therefore we separately identified the frequency of on-farm (Fig. 3B) and off-farm measures per cell (Fig. 3C). Specific locations have a high frequency of on-farm measures, especially in and around orchards. These locations are thus identified, across the different runs, as priority areas for implementing both agri-environment measures, but more specifically for on-farm measures. Interpretation should be done carefully as the locations embed different trade-offs. The frequency for off-farm measures per location was far lower (Fig. 3C) indicating that no location is clearly a priority to be taken out of production. Thus although a combination of both on-farm and off-farm measures is preferred, only priority locations for on-farm measures could be identified.

3.3. Comparison to current and regional policy

The conservation plan resulted in a 15.54% increase in newt habitat compared to the current landscape, at the cost of a 37.21% decrease in pasture production (Fig. 4). The conservation plan is primarily designed for species protection and the increase in newt habitat highlights that the plan is relatively effective in this regard. However, the conservation plan addresses more species beyond the newt which we cannot incorporate in our comparison given the model limitations. For the other objectives the conservation plan did not improve the aesthetic value of the landscape (0%) and decreases fruit yield (−19.35%). Fruit yield strongly declined because a small set of orchard fields is taken out of production in the current conservation plan.

We compared both the current landscape and conservation plan to the results from the optimization analysis. One has to be aware that the landscapes were somewhat different because the current and nature conservation plan allocates measures at the cell level whereas the optimization analysis has homogeneous LULM (allocation) at the farm level. Nonetheless both the current landscape and the conservation plan could be further optimized for all four objectives (Fig. 4). For the current landscape there were multiple Pareto-optimal land allocations that performed better on the environmental objectives, without reducing pasture production. For example, compared to the current landscape a different LULM allocation could increase newt habitat (+22%), reduce pasture production loss (+22%) and simultaneously increase the other environmental objectives.

For the conservation plan there were also multiple Pareto-optimal land allocations that performed better on the environmental objectives, without reducing pasture production. Compared to the conservation plan a different land allocation resulted in a smaller loss in pasture production (−37.21% vs −34.74%) and additional increases for all three environmental objectives (orchard: +22.94%, aesthetics: +0.83%, newt: +25.85%). These results highlight that combining on-farm and off-farm measures can further increase newt habitat with smaller losses in pasture production compared to the conservation plan. In addition, fruit yield and landscape aesthetics could be increased alongside newt habitat in the Kromme Rijn Area.

4. Discussion

A landscape optimization for multiple objectives is capable of identifying functional trade-offs between competing objectives (Lautenbach et al., 2013). Previous analyses optimized the landscape allocating multiple management options but did not break the separate effects of each option apart (Lautenbach et al., 2013; Pennington et al., 2017).
As a result, we found that all agri-environment measures could improve all environmental objectives simultaneously, but that the improvement of each objective differed between on-farm and off-farm measures. Either choosing a management strategy focused on “off farm” or “on farm” resulted in a strong trade-off between newt habitat and fruit yield. Allowing a mixture of measures could alleviate this trade-off. This provides important information for landscape planners, as it does not only show that trade-offs exist, but more importantly, it shows how these trade-offs can be effectively navigated through relevant agri-environment measures.

All three environmental objectives were sensitive to landscape configuration including functions related to surrounding landscape (distance decay), edge effects and linear elements. The importance of landscape configuration for ecosystem services has been previously addressed using a conceptual model (Mitchell et al., 2015) or model comparisons (Lautenbach et al., 2011; Verhagen et al., 2016). The Pareto-frontier in any optimization analysis can be interpreted as the set of optimal landscape configurations for increasing opportunity costs. It highlights what can be optimally achieved when combining the effect of the area of interventions (composition) with the spatial allocation (configuration). In addition, our results highlight the importance of linear elements in agricultural landscapes for ecosystem service supply. Increases in newt habitat suitability and aesthetic quality of the on-farm experiment can be solely attributed to increasing the amount of linear elements given that organic farming has no impact on these objectives in our models. Previous research linked these elements to a diverse set of ecosystem services and argued for the inclusion of elements in landscape optimization approaches (Jones et al., 2013; Verhagen et al., 2016). To our knowledge this is the first application of linear elements in landscape optimization. More importantly, we demonstrated that a landscape optimization without these elements would result in a less optimal outcome (Fig. 2), thus providing evidence for the importance of accounting for configuration and linear elements in landscape planning.

In this paper, we attempted to bridge the gap between multi-objective optimization resulting in numerous alternative land allocations and specific spatial planning recommendations. Any multi-objective optimization will result in a large set of Pareto-optimal solutions (Karakostas, 2017) and previous research has translated these numerous outcomes into spatial planning recommendations by providing example landscapes along the Pareto-front (Gouvevitch et al., 2016; Kennedy et al., 2016; Nelson et al., 2009; Pennington et al., 2017). A method to effectively visualize optimization outcomes can help to discuss policy targets (Verburg et al., 2016). Based on additional constraints and discussions with stakeholders, one could potentially arrive at a single optimal LULC allocation. However, such an approach is criticized for not showing the pathways to reach such outcomes (Verburg et al., 2016). Here, we have aggregated all optimization outcomes to identify priority areas for agri-environment measures, following an approach by Karakostas (2017). By using all optimization

Fig. 4. The set of Pareto-optimal solutions for the “all options” experiment relative to the current landscape (C). NBP refers to the nature conservation plan. Compared to C and NBP, the whole set of areto solutions scores better in terms of aesthetics (lower central panel) and orchard production (lower right panel). Therefore, in the top and lower left panel, all solutions to the upper right of C or NBP score better on all objectives compared to the current landscape or the nature conservation plan, respectively. The results depicted are the outcomes of the “all options” experiment.
results we could move beyond visualizing a few exemplar landscapes only. The major advantage is the possibility to directly delineate target areas and LULM options that are Pareto-optimal for the specific planning context. Such information can be more readily used in policy design and spatial planning processes, which can subsequently benefit from the advantages of optimization studies.

Condensing the full set of Pareto-optimal solutions into a single spatial map, however, risks ignoring important trade-offs and preferences between the solutions. The involvement of relevant stakeholders before (a priori), during (interactive) or after (a posteriori) the optimization process is vital, to understand the local decision making context, as well as to provide a suitable fit with local interests and ecosystem services demand (e.g. Bryan et al., 2010; Cord et al., 2017).

In addition, understanding the needs of planners and policy makers is also an important factor for a successful policy uptake of this type of decision-support tools (e.g. McIntosh et al., 2011; Albert et al., 2014). Therefore identification of priority areas for restoration has the potential to inform policy makers and stakeholders by providing spatially explicit information on the location of restoration measures but should not be easily used as a technical replacement of stakeholder deliberation as tradeoffs may be judged in different ways by different stakeholders and other considerations, not accounted for in the optimization, may play an important role. One step to better include stakeholder deliberation in the approach is to assign relative weights to each outcome, instead of assuming an equal weight for all alternatives, as it is done in our identification of priority locations. Therefore, care should be taken in not interpreting the highest priority areas for restoration as a single best solution but as a way of presenting optimization results in a spatially explicit manner and to inform and not end a discussion among stakeholders.

4.1. Limitations to our approach

Any environmental model and computational optimization requires a set of simplifications and assumptions. In our case, a limitation is the necessity to implement LULM alternatives at the farm level. This assumes a uniform LULM across all cells in a farm. However, in reality many agri-environment measures can be implemented below the farm level. Therefore, the resolution at which the optimization model and the landscape planner allocate LULM is not aligned. A clear example of this is the establishment of linear elements, which in reality does not necessarily occur on all fields of a farm. We partly accounted for this by only allowing allocation of linear elements on field edges.

An importation decision is the use of the optimization algorithm, in our case NSGA-II. Several optimization algorithms exist that can be used for multi-objective optimization such as BORG, SPEA-2 or NSGA-III (Cholodowicz and Orłowski, 2017; Deb and Jain, 2013; Hadka and Reed, 2015). Here we choose to use the NSGA-II given the broad application in spatial allocation problems (Malczewski and Rinner, 2015).

Our analysis focuses on the use of optimization algorithms in a real world case study and policy framework. A methodological comparison of individual optimization algorithms is outside the scope of this paper. Importantly, using NSGA-II algorithm we can highlight that both the current situation and the nature conservation plan can be optimized for multiple objectives in our study area.

Any optimization model depends on the quality of the underlying models used to calculate the individual objectives. A first clear limitation of our approach is that we used a single species model as a proxy for biodiversity. The great crested newt is an important focal species for our study area and much effort goes into habitat protection and restoration for this particular species. Therefore, it has a direct policy relevance for our study area. However, the great crested newt should not be interpreted as a proxy for overall response of biodiversity, given its strict reliance on the combination on habitat restoration in the vicinity of ponds. A second limitation is that we used average production values to quantify both pasture and orchard production. For orchard production the production values are based on local case studies in similar regions. For pasture production we used national averages given a lack of more specialized data. Given the relatively small extent of the study area and the similarities in management intensity across the region a single average pasture production value was deemed a valid assumption. A third limitation is that we used social media pictures as a proxy for aesthetic quality. The use of this proxy might introduce a bias to specific users of the area as well as to specific aesthetic qualities particularly suitable to capture through photos. The major advantage of this model is that it was specifically developed for this study region (Tieskens et al., under review).

4.2. Management recommendations

The current nature conservation plan focuses on taking designated areas out of production to meet species conservation objectives. Here we showed that with a more optimal allocation of measures, it was possible to meet species conservation objectives while simultaneously improving on a number of other environmental objectives. Moreover, we showed that the addition of on-farm measures in combination with off-farm measures is more effective in realiseing the objectives. The nature conservation plan combines taking designated areas out of production with promoting voluntary measures on agricultural land. We showed that explicitly incorporating on-farm measures could be a more effective strategy. Focusing on establishment of linear elements and organic management might be more easily implemented because it involves lower costs to farmers, as well as the possibility to obtain financial support for establishing linear elements.

In addition, our spatial analyses showed that priority areas for agri-environment measures do not align with currently designated areas. These results can assist spatial planners in designing future plans. The current management strategy focuses on farms forming voluntary collectives proposing to implement agri-environment measures. Spatially explicit knowledge on the location of priority locations for restoration can help evaluate the effectiveness of these proposals.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.03.013.

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