Exploring Trade-offs Among Environmental Services to Support Landscape Planning

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EXTENDED ABSTRACT

Spatial planning of land-use and human activities for natural resource management often involves many stakeholders, each with their own values and preferences, and complex biological processes. We present an exploratory approach named Landscape IMAGES, which can be employed to determine interactions among various environmental services. These services can represent productive, economic, cultural or ecological dimensions of (agro-)ecosystems in landscapes or small regions. The approach provides insight in the full range of possible futures without prioritizing preferences beforehand. Moreover, it offers room for discussion and perspective sharing, to inform decision making and to increase understanding and support of stakeholders.

The methodology of Landscape IMAGES is illustrated with an example of the redesign of an agri-ecological zone in the Netherlands, where economical, ecological and culture-historical aspects were considered. The aim of research involvement was to support an NGO involved in landscape management with the evaluation of a sketch design landscape plan of adjustments to the hedgerow structure typical of the landscape. To offer insight in the quality of the landscape plan the following landscape characteristics and their interactions were explored:

- Ecological quality, with connectivity (largest connected sub-graph) of the hedgerow structure for dispersal of animal species as an indicator.
- Landscape identity, with indicators for variation, naturalness and historical configuration of the hedgerows.
- Landscape maintenance costs for farmers spent on removal, planting and recurrent maintenance of hedgerows.

The resulting seven indicators reflect environmental services (or functions) of the landscape and served as objectives in a multi-objective decision problem. To solve this problem we used a heuristic technique: the evolutionary strategy of Differential Evolution. This technique yields a set of solutions, each representing a spatial configuration of hedgerows in the landscape, which determines the performance of environmental functions, and thus the quality of the solution. The solution set is randomly initialized and iteratively improved by generating a competitor for each solution in the set with evolutionary operators of mutation, uniform cross-over and selection. The selection processes uses the Pareto optimality concept to rank solutions. A set of Pareto optimal solutions consists of solutions that are not dominated by other solutions, when all objectives are considered.

By plotting the performances of the solution set interactions between the objectives were determined. By identifying in the solution space both the original landscape and the sketch design landscape plan it became clear that the decision rules employed by the NGO impacted positively on connectivity. However, the values of indicators of landscape identity were slightly reduced by the implemented redesign. The solutions indicated opportunities for improving these objectives simultaneously.

By exploring trade-offs among objectives, the Landscape IMAGES modelling instrument aims to reveal the ‘manoeuvring space’ of decision makers on land use issues, thus contributing to solutions that do justice to interests of broad groups of stakeholders. This methodology is applicable to any design problem characterized by multiple scale spatial interactions.

1. INTRODUCTION

Spatial planning of land-use and management activities in natural or rural regions aiming at sustainable natural resource management, in rural landscapes combined with agricultural production, is in many occasions much debated. This is due to the high number of involved stakeholders, with often strongly contrasting perspectives and expectations for future developments in a region (Kangas et al., 2005). To complicate matters, scientific understanding of biological processes governing environmental functions in complex agro-ecosystems and the possibilities for site-specific model application and prediction are generally limited (Carpenter et al., 2006).

In such situations scientists could play a role to inform the debate. As a first step, scientists and planners may attempt to make interactions between the demanded environmental functions explicit and preferably assist the decision making process by feeding the discussions with sketches of possible futures for a given case study region. The second step would be the selection of acceptable designs for implementation, preferably without assigning often arbitrary weights to the importance of the various environmental services in an early stage of design, to stimulate acceptance by the involved stakeholders. Therefore, the selection process should be able to identify the designs that satisfy the requirements as well as possible, while eliminating inferior solutions (Das, 1998).

A widely applied planning method is the construction of sketch designs based on narrative development scenarios (e.g., Münier et al., 2004) or optimization studies (e.g., Annets and Audsley, 2002). However, these designs represent individual points in the solution space the extremes of which are defined by the trade-off between the different environmental functions. Optimization studies and existing multi-criteria approaches for spatial planning perform no systematic exploration of the solution space. As a consequence, the currently used methods fail to clarify the interactions between environmental functions and present a narrow view of the future possibilities, addressing only a limited number of perspectives (Carpenter et al., 2006).

We developed the Landscape IMAGES methodology (Groot et al., 2007) to explore the whole solution space for multi-scale spatial planning problems comprising spatial interactions, and enables the identification of a limited number of most desirable designs. In this paper we present the methodology and an application to the redesign of hedgerow structures in an agri-ecological zone in The Netherlands.

2. METHODOLOGY

2.1. Conceptual Model

The assessment of the performance of a given farm or landscape is based on multiple criteria, which can represent productive, economic, cultural or ecological dimensions of (agro-)ecosystems in landscapes or small regions. Different land-use activities make different contributions to the performance criteria and the activities on two or more spatial units may interact with respect to the performance criteria. Consequently, different spatial configurations of activities result in different values of the performance criteria. The exploration of the trade-offs among performance criteria or objectives can be formulated as a multi-objective design problem, which can be generally stated as follows.

$$\text{Max } F(x) = (F_1(x),...,F_k(x))^T \qquad (1)$$

$$x = (x_1,...,x_n)^T \qquad (2)$$

Subject to i constraints:

$$g_i(x) \leq h_i \qquad (3)$$

Where, $F_1(x),...,F_k(x)$ are the objective functions that are simultaneously maximized or minimized, and $(x_1,...,x_n)$ are the decision variables that represent the activities allocated to the n spatial units. The decision variables can take on values from a predefined array $x \in S$, where S is the solution or parameter space. Constraints (Eq. 3) can arise from the problem formulation, for instance by limitations on the inputs or outputs related to the activities. Heuristic techniques such as genetic algorithms (GAs) and evolutionary strategies (ESs) can be employed to obtain approximations of the trade-off surfaces by a population of solutions, each representing a configuration of activities for the landscape.

2.2 Pareto-based Differential Evolution

The trade-offs among the objectives were explored with a multi-objective implementation of the ES algorithm of Differential Evolution (DE) developed by Storn and Price (1995). Currently, DE is widely used in the research community due to its simplicity, efficiency and robustness (Mayer et al., 2005). DE involves the iterative improvement of a set of solutions or genotypes. Each allele in the genotype is a real number. In our application, the genotypes represented alternative landscapes, and the alleles were decision variables in which the land-use of an individual field and the occupation of the field borders were encoded.

A genotype is a multi-dimensional vector $p=(p_1,...,p_s)^T$ of s alleles. Each allele p_i is initialized as $p_{i,0}$ by assigning a random number within the allowed range:

$$p_{i,0} = L(p_i) + r_i\,(U(p_i) - L(p_i)) \qquad (4)$$

Where r_i denotes a uniformly distributed random value within the range [0,1] and L and U are the lower and upper values of the allowed range. A new generation x+1 is created by applying mutation and selection operators on the individuals in the population P of genotypes of the current generation x. The first step of the reproduction process is generation of a trial population P' that contains a counterpart for each individual in P, that is produced by parameterized uniform crossover of a target vector and a mutation vector. The mutation vector is derived from three mutually different competitors c_1, c_2 and c_3 that are randomly selected from the population P in the current generation x. The allele values are taken from the mutation vector with probability C_R:

$$p'_{i,x+1} = \begin{cases} c_3 + F \times (c_1 - c_2) & \text{if } r_i < C_R \\ p_{i,x} & \text{otherwise} \end{cases} \qquad (5)$$

The parameter $F \in [0,2]$ is a parameter that controls amplification of differential variations. After a mutation, the value of $p'_{i,x+1}$ can extend outside of the allowed range of the search space. For allele values that violate the boundary constraints the repair rule presented in Equation 6 is applied. This rule implements a mechanism that can be denoted as 'back folding': the adjustment for the allele is calculated by interpolation into the allowed range from the boundary by a value that is proportional to the difference between the boundary and violation values:

$$p'_{i,x+1} = \begin{cases} L(p_i) - \dfrac{p'_{i,x+1} - L(p_i)}{F} & \text{if } p'_{i,x+1} < L(p_i) \\ U(p_i) - \dfrac{p'_{i,x+1} - U(p_i)}{F} & \text{if } p'_{i,x+1} > U(p_i) \\ p'_{i,x+1} & \text{otherwise} \end{cases} \qquad (6)$$

A trial genotype $p'_{i,x+1}$ replaces $p_{i,x}$ if it has a better ranking or is in a less crowded area of the search space (see below) than the parent genotype. Population size N is determined by the multiplication factor M (N=s×M). The last parameter is the number of generations G, which serves as the stopping criterion.

The first criterion for replacement of individuals by a trial solution is the Pareto-based ranking. The ranking mechanism proposed by Goldberg (1989) is employed to evaluate the fitness of the individuals. Rank 1 is assigned to the non-dominated individuals and thus represents highest fitness values in the population. These individuals are removed from contention. A new set of non-dominated individuals in the rest of the population are ranked as 2 with next highest fitness values, and so forth until all of the individuals in the population are assigned a rank. An individual is replaced if the trial solution has a better ranking.

The second criterion is the Pareto efficiency. A solution has a superior Pareto efficiency, if both solutions $p_{i,x}$ and $p'_{i,x+1}$ are of the highest Pareto rank. A solution is efficient of order k ($1 \leq k \leq n$, where n is the number of objectives) if it is not dominated by any other solution in the k-element subsets of objectives. This is an extension of the ordinary concept of Pareto optimality (Das, 1998).

The third criterion for selection of trial solutions is the crowding distance metric proposed by Deb et al. (2002). This metric θ represents the within-rank solution density and is calculated from the normalized distance for each objective between adjacent solutions in the search space, as follows:

$$\theta = \sum_{j=1}^{k} \frac{\left|d_i - \bar{d}\right|}{\left|B_j\right|} \qquad (7)$$

In this equation, B_j is the boundary for objective j, which can be estimated from the difference between the minimum and maximum objective values along dimension j in the first rank. Parameter d_i denotes the Euclidian distance between two consecutive solutions within the Pareto front of a given rank. The parameter $\bar{d}$ is the average of these distances. An individual is replaced by a trial solution of the same rank if the latter has a higher value of θ (Deb et al., 2002). This criterion promotes the spread of solutions within the objective space.

2.3 Landscape optimization problem

We applied this methodology to support the restructuring of an ecological zone of 873 ha in the Northern Frisian Woodlands, the Netherlands. To assist the regional non-governmental landscape management organization (NGO) responsible for planning and implementing of the restructuring, their landscape plan was evaluated and alternatives were generated.

The region where the ecological zone is located is characterized by a small scale landscape on predominantly sandy soils with dairy farming as the prevailing land-use activity. On some farms a limited proportion of up to 5% of the area is used for forage maize production, while the rest of the area is occupied by permanent grassland, rotationally grazed and mown. The fields with an average size of two hectares are often surrounded by hedgerows. The aim of this project was to improve the ecological significance of the landscape for species dependent on hedgerows and to restore the historical character of the landscape by targeted, cost-effective additions to the hedgerow structure.

The landscape configurations generated for this case study represent the placement of hedgerows in the case study area. We aimed at supporting the NGO in designing an improved hedgerow structure in the agri-ecological zone, taking into account seven objectives relating to increasing the ecological quality (a. connectivity of the hedgerow structure for animal species dispersal) and landscape identity (maintaining b. variation, c. naturalness and d. historical configuration of hedgerows in the landscape) and to decreasing maintenance costs for farmers for e. removal, f. planting and g. recurrent maintenance of hedgerows.

a. The connectivity of the hedgerow structure is reflected in the integration of the length of largest connected sub-graph (Urban and Keitt, 2001) over a range of dispersal distances. This was used as a measure of ecological quality and was maximized.

b. Sight lines are defined as the distance between two consecutive hedgerows in the longitudinal direction of the fields. As the variation in the sight lines determines the perception of the landscape as ‘half-open’, this variation was maximized.

c. Sight lines from road to road through the landscape are perceived to disturb the ‘naturalness’ of the landscape. These sight lines determine the landscape porosity, which was minimized.

d. Historically, the landscape has developed to have a high ratio of longitudinal hedgerows over transversal hedgerows relative to the cultivation and parcelling direction, the L/T ratio. To maintain this characteristic the L/T-ratio was maximized.

e. The removal of existing hedgerows can disrupt the historical characteristics of the landscape and is costly. Therefore, the removal of hedgerows was minimized.

f. The addition of new hedgerows is costly, therefore in the optimization the placement of new hedgerows was minimized.

g. From the perspective of some farmers aiming to develop large-scale industrial farming systems, the presence of hedgerows forms a barrier to manoeuvre with machines and for enlargement of fields. Moreover, for these farmers the hedgerows are unwanted sink of labour for maintenance. To represent this business-economic perspective, one of the objectives is to minimize the total hedgerow length.

The results of the multi-objective explorations were compared with the performance of the original hedgerow configuration in the case study area and the implemented landscape plan developed by the landscape management organization.

3. RESULTS

Solution set covers a large range of possible landscape configurations in terms of land-use on fields and the placement of hedges on field borders. In Figure 1a this is illustrated for total hedgerow length, which was found to be strongly but not fully correlated with landscape connectivity.

By identifying in the solution space the original landscape and the restructured landscape it became clear that the decision rules employed by the NGO impacted positively on connectivity. The results made clear that further improvements would have been feasible without increasing the length (and therefore costs) of hedgerows in the landscape (Figure 1a).

The results also describe the contribution to the various objectives of one additional unit of hedgerow length, thus providing input for negotiations of the NGO with donors about biggest ‘bang for a buck’.

The solutions that were classified as the ‘best compromises’ among the various objectives on the basis of preference ordering (Pareto efficiency) entailed some removal of hedgerows and sometimes a slight reduction of connectivity compared to the original situation (see Figure 1a), but maintaining the landscape identity, as illustrated for the L/T ratio in Figure 1b. Clearly, this characteristic was compromised by the implemented landscape plan of the NGO, which involved the planting of most of the new hedgerows transversal to the parcelling direction.

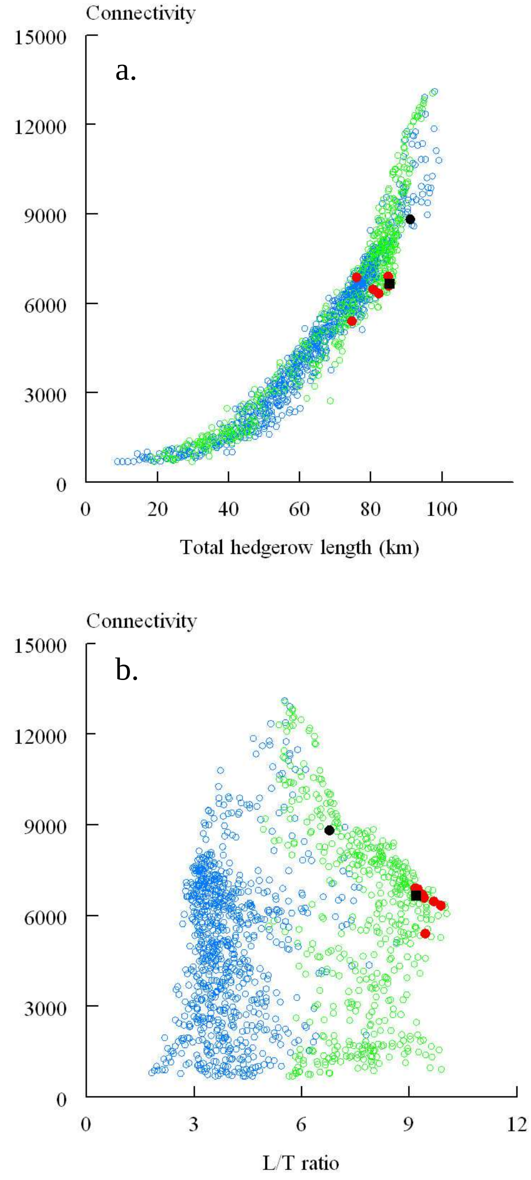

Figure 1. Connectivity of the linear landscape elements in the case study area in relation to total hedgerow length (a) and the ratio between hedgerows longitudinal and transversal to the cultivation and parceling direction (L/T-ratio, b). Each point represents a configuration of the hedgerows with Pareto efficiency of k=7 (blue), k=6 (green) or k=5 (red). The performances for the original situation (■) and the landscape plan (●) are indicated.

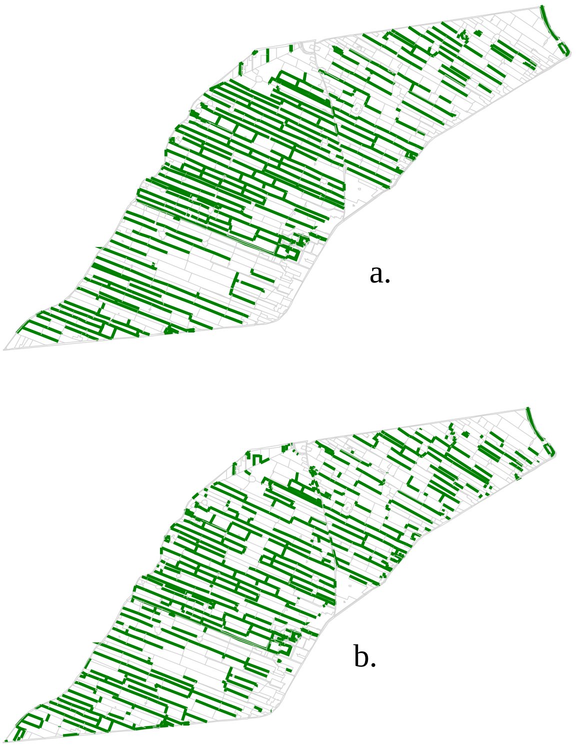

Figure 2. Original hedgerow configuration in the 873 ha case study region in the Northern Friesian Woodlands (a) and a generated landscape (b) with similar hedgerow length (85.6 km in a and 85.7 km in b) and connectivity (6.7 and 6.9), but strongly contrasting ratio between longitudinal and transversal hedges (8.79 in a and 5.75 in b) and porosity (45 and 15).

Figure 2 demonstrates the different contributions to landscape quality in terms of porosity, and cultural history in terms of the L/T ratio of two landscapes similar in economic and ecological performance, expressed in hedgerow length and connectivity, respectively. The perception of the two landscapes by visitors will be very different, highlighting the need to include multiple objectives in approaches for negotiation support.

4. DISCUSSION

The results of the explorations provided a clear insight in the interactions between the selected environmental services, as illustrated for connectivity (ecological dimension), L/T ratio (culture-historical dimension) and total hedgerow length (economic dimension) in Figure 1. This was judged as very informative by the landscape management NGO. For the NGO, the joint development of the methodology resulted in increased insight in their 'rules-of-thumb' for landscape planning in agri-ecological zones, and gave inspiration for using new rules and constraints in their planning process.

By exploring trade-offs among objectives, the Landscape IMAGES modelling instrument aims to reveal the 'manoeuvring space' of decision makers on land use issues, thus contributing to solutions that do justice to interests of broad groups of stakeholders. We have previously used linear programming based approaches (Rossing et al., 1997) in combination with nearly-optimal solutions (Makowski et al., 2001) but found this more cumbersome than using Pareto-based Differential Evolution. An additional benefit of the latter method is its tolerance to different specifications of the optimization problem. Programming methods fall short when faced with large combinatorial problems. Evolutionary computation is a useful compromise for the type of complex decision problems presented here where interest is more in trends and variation in the solutions than in precise optimality.

An area for development is selection and presentation of subsets of solutions in the multi-dimensional solution space that matches viewpoints of stakeholders. Here, preference ranking on the basis of priority assigned to objectives may provide new directions to connect land-use as described in this section to the demand for economic, ecological and social functions by society. Thus, the flexibility of multi-objective evolutionary computation offers opportunities for connecting different spatial scales as well as different scientific disciplines to create new perspectives for sustainable land use. Future applications will rely on increased algorithmic efficiency, particularly in view of sparse solutions spaces associated with high numbers of objectives, and techniques to select and present relevant solutions in the discussion and negotiation process.

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