Exploring ecosystem services trade-offs in agricultural landscapes with a multi-objective programming approach

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Model-based exploration of trade-offs and synergies among ecosystem services in agricultural landscapes – a Pareto-based multi-objective optimization approach

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Highlights

- Landscape IMAGES is a flexible framework for spatially explicit analysis of landscapes
- Landscape IMAGES uses a Pareto-based optimization algorithm to explore tradeoffs
- The use of object-oriented programming and design patterns allows easy extension
- Large sets of landscapes can be generated to inform discussions among stakeholders
- Landscapes can be visualized and further analyzed before selection and implementation

Abstract

In this paper, we present the LandscapeIMAGES modeling framework for multi-scale spatially explicit analysis of tradeoffs and synergies among ecosystem services provisioning across agricultural landscapes. The framework generates large sets of spatially explicit land-use and management scenarios to inform discussions among stakeholders involved in landscape planning processes. The generated plans are evaluated and optimized for multiple indicators of ecosystem services provisioning. The framework has been developed with an object-oriented programming approach to allow rapid implementation of new indicators and application to new case study landscapes. The modeling system includes (i) a generic framework for Pareto-based multi-objective optimization to generate a set of land-use and management plans, (ii) an easily expandable collection of modules to quantify indicators of ecosystem services provisioning, which can be used as objectives or constraints in optimization, and (iii) a graphical user interface that allows parameterization of the model and inspection of the original and generated land-use and management plans. This allows visualization of trade-offs and synergies among ecosystem services as a consequence of land-use and management planning choices. LandscapeIMAGES is currently used in projects aiming to improve the provision of multiple ecosystem services within landscapes in Asia, Africa, Latin America and Europe.

Keywords: Landscape design; Pareto-based multi-objective Differential Evolution; ecosystem services; multifunctional landscapes.

1. Introduction

The provisioning of ecosystem services (ESs) by agricultural landscapes is highly correlated with the types of landscape elements and their spatial arrangement (Carrara et al., 2015; Neumann et al., 2016; Veres et al., 2013). Thus, not only landscape composition but also landscape structure affect ESs such as biodiversity conservation, erosion control, aesthetic value, carbon sequestration, pollination and bio-control of pests and diseases (Groot et al., 2012; Rostami et al., 2016; Steckel et al., 2014). Identification of desirable alternatives for current structure and composition of agricultural landscapes can be supported by insights from tools that assess trade-offs and synergies among ESs under alternative land-use and management scenarios. Such insights can also support negotiation among actors involved in land-use and management planning (Giller et al., 2011; McShane et al., 2011). In-situ experiments to reveal the relation between ecosystem services on the one hand and landscape structure and composition on the other are generally considered infeasible, and recourse has to be taken to *in silico* approaches. Various software tools have been developed over the past decade to support analysis and design of landscapes. These tools have typically addressed sets of ecosystem services that were fixed by the tool developers (e.g., Mellino and Ulgiati, 2015; Peh et al., 2013; Rostami et al., 2016; Summers et al., 2015; Zambelli et al., 2012) resulting in a lack of flexibility and applicability. Furthermore, these tools generally only enable scenario-based simulations, which, by definition, address only a limited number of land-use and management alternatives (Jackson et al., 2013; Tallis et al., 2011).

Pareto-based multi-objective Differential Evolution (P-MODE), from the family of heuristic optimization algorithms, is well-suited for exploring trade-offs and synergies among indicators of landscape ESs (Behera and Rana, 2014; Groot et al., 2009, 2012). The P-MODE algorithm finds a set of Pareto-optimal solutions rather than a single weighted optimal solution for a multi-objective problem (Abbass and Sarker, 2002; Xue et al., 2003). A solution, in this case a possible land-use and management scenario across an agricultural landscape (defined in terms of its structure and composition), is called Pareto-optimal when its performance in terms of a particular indicator cannot be improved without deteriorating the performance in terms of one or more other indicators. The Pareto-optimal set of land-use plans, therefore, represents the trade-off among the chosen indicators of ESs. In some cases, multiple indicators may be improved simultaneously, revealing synergies (Groot et al., 2009). The current land-use across the agricultural landscape is not usually part of the Pareto-optimal set, and options for improvement of multiple indicators (win-win options) by changing land-use and management in the landscape are readily identified in the generated set (Groot et al., 2007, 2012; Groot & Rossing, 2011).

We implemented the P-MODE algorithm in a modeling framework for exploration of Pareto-optimal landscapes, called LandscapeIMAGES. The framework allows incorporation of any number, and type, of indicators of ESs, effectively tackling the limitations of flexibility and applicability of other existing approaches. Here we present the key features of LandscapeIMAGES and its current applications for exploring trade-offs and synergies between multiple objectives for ESs in agricultural landscape design.

2. Modeling system

LandscapeIMAGES (LI; Interactive Multi-goal Agroecosytem Generation and Evaluation System) has been developed using the object-oriented software development paradigm to facilitate maintenance, reuse and easy addition of components, as the tool was intended to be generically applicable in multiple case studies and regions. The framework belongs to metaheuristics (Memmah et al., 2015) and consists of two main parts: (i) the system domain which constitutes the generic framework that incorporates databases, GIS libraries, and the P-MODE optimization algorithm, and (ii) the application domain that is designed to enable implementation of modeling routines and decision rules to address optimization objectives for a landscape (Figure 1). Each structural element in an agricultural landscape (fields, borders, roads, rivers, etc.) can be represented by a GIS polygon; linear elements like field borders and hedgerows can be represented by GIS line elements. Characteristic data about each landscape element is loaded as an internal attribute table of the GIS file. Data about alternative properties (e.g. vegetation type, land-use) and management of the landscape elements are stored in MS-Access/SQLite database tables.

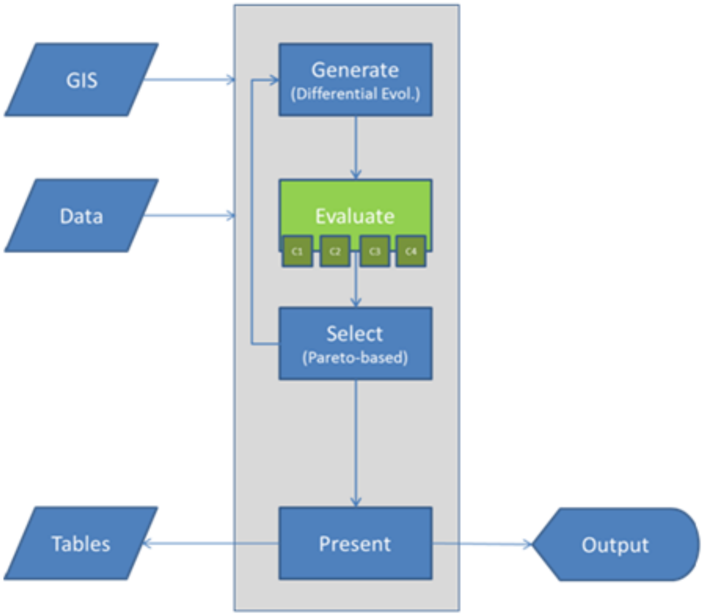


Figure 1. Configuration of the LandscapeIMAGES framework. 'GIS' represents one or more shape files containing layers with landscape elements and 'Data' represents MS-Access/SQLite database tables storing properties of landscape elements. 'Generate', 'Evaluate' and 'Select' represent procedures in the heuristic generation of land-use and management plans (Generate), followed by indicator computation (Evaluate) and Pareto-based ranking and replacement (Select). The ‘Evaluate’ procedure comprises a flexible collection of components (indicated as C1-C4) that perform quantification of ecosystem service indicators relevant to the problem studied. 'Present' represents the visualization of solutions in the resulting set of optimized land-use and management plans. The layout of resulting land-use and management plans can be saved as database tables ('Tables') or shown in the graphical user interface ('Output').

In the following sections, we describe the conceptual approach of the framework for landscape exploration and design as the system domain (Section 2.1) and the technical possibilities for developing new applications to landscape-design case studies as the application domain (Section 2.2). The graphical user interface is briefly addressed in Section 3. In Section 4 we present a case study as an illustration of the application of the LI framework.

2.1. System domain

The system domain comprises the generic aspects in LandscapeIMAGES and links the P-MODE algorithm for multi-objective optimization with the GIS library and the data-access layer to communicate with relational databases. The GIS library interfaces with the files that store spatial information and properties of landscape elements. Additionally, the GIS library handles spatial computations, such as neighborhood, distance, area, perimeter and aggregation operations, on a spatial data file. The relational databases (Codd, 1990; Date, 2004) store generic model parameters (for instance related to the settings of optimization algorithm) and case study specific characteristics of modeled landscape processes. After simulation, desirable generated land-use and management plans can be saved in tables in the database system or as maps.

Exploration of trade-offs and synergies among ecosystem service indicators is formulated as a multi-objective optimization problem that can generally be represented by equations (1-3).

$$Max\,\boldsymbol{U}(\boldsymbol{x}) = (U_1(x), U_2(x), \ldots, U_k(x))^T \qquad (1)$$

$$\boldsymbol{x} = (x_1, x_2, \ldots, x_n)^T \qquad (2)$$

Subject to i constraints:

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

Where $U_1(x), \ldots, U_k(x)$ are the objective functions that are simultaneously maximized or minimized, and $x_1, \ldots, x_n$ are the decision variables that define alternative land-use and management options that can be assigned to landscape elements. Examples of decision variables are alternative land uses for linear landscape elements, and alternative management systems for various crops. Detailed descriptions of implementation of this algorithm are given in Groot et al. (2007, 2010, 2012).

The optimization algorithm used is based on a class of heuristic algorithms denoted as evolutionary algorithms. Heuristic optimization algorithms are often inspired by processes in nature. For instance, simulated annealing is inspired by the processes associated with controlled cooling of metals, while ant colony optimization is based on search processes of ants. The procedures are called heuristic because there is no formal mathematical guarantee of convergence to the optimal solution, as is the case for so-called mathematical programming methods, such as linear programming. Using the metaphor of evolution, the evolutionary algorithm generates new land-use and management plans by exchanging values of decision variables between two existing landscapes (‘cross-over’) and randomly changing the value of selected decision variables (‘mutation’).

The optimization algorithm is implemented in the DEOptimizer class that manages a population of solutions consisting of two, equally sized, sets of decision variables $(x_1, \dots, x_n)$ that define the configuration of the land-use and management: the selected set and the competitor set. In each iteration, the optimization algorithm:

(i) Generates a new set of competitors (one competitor for each solution in the selected set) using uniform crossover governed by two parameters for the crossover probability (CR) and amplitude (F) (Storn and Price, 1997). CR represents the probability that a decision variable is adjusted, while F defines the relative magnitude of the adjustment in the value of the adjusted decision variable.

(ii) Calls the Evaluate method for each solution to translate the values of the decision variables into the configuration of a new land-use and management scenario. Performance indicators that serve as objective function values for the landscape are then computed and checked whether they meet the constraints that were set by the model user, e.g. maximum areas under a particular land use, maximum allowed emission rates or minimum desired financial revenues.

(iii) Performs a pair-wise comparison of the land-use and management plans in the selected set and the competitor set, and replaces the selected set of decision variables with the competitor set if the competitor performs better. In this step, the performance of a land-use and management scenario is expressed in terms of its Pareto rank (explained below). Land-use and management plans with lower Pareto rank, or those that differ strongly from already generated land-use and management scenarios are favored over alternatives.

Two Pareto ranking procedures can be used (Figure 2), and are applied to the whole population of generated land-use and management scenarios, i.e. the combined sets of selected and competitor alternatives. Simulated land-use and management scenarios in the population are non-dominated when they do not perform worse than any other individual for all the objectives, i.e. when they perform equal to or better than any other individual in at least one objective (Figure 2a). If the aim of the optimization is to improve relative to an existing landscape configuration, an extended ranking scheme can be applied, which prioritizes solutions that perform better than the original configuration for all objectives; these are assigned the superior rank 0, as displayed in Figure 2b.

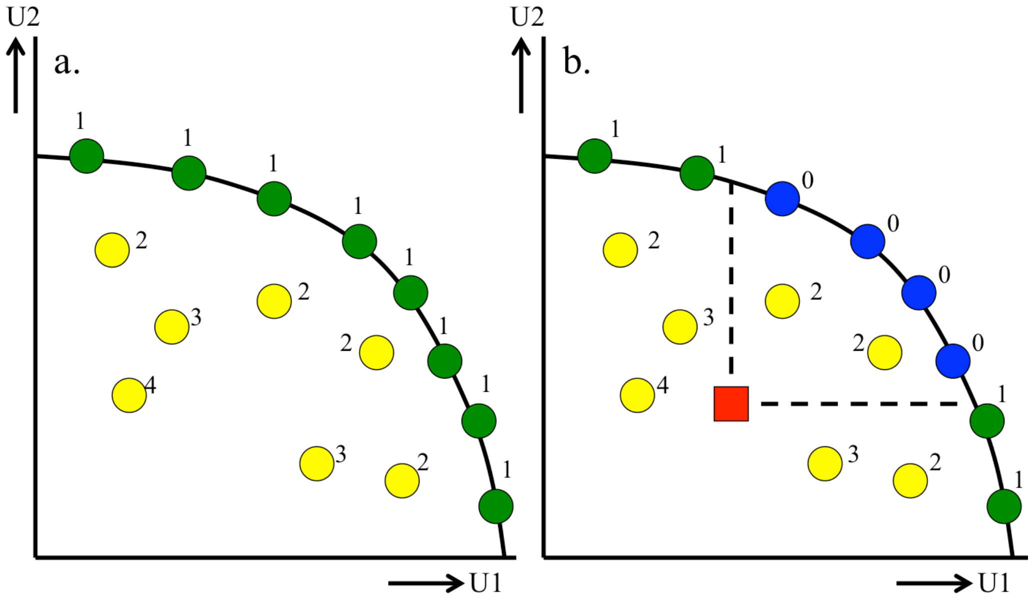


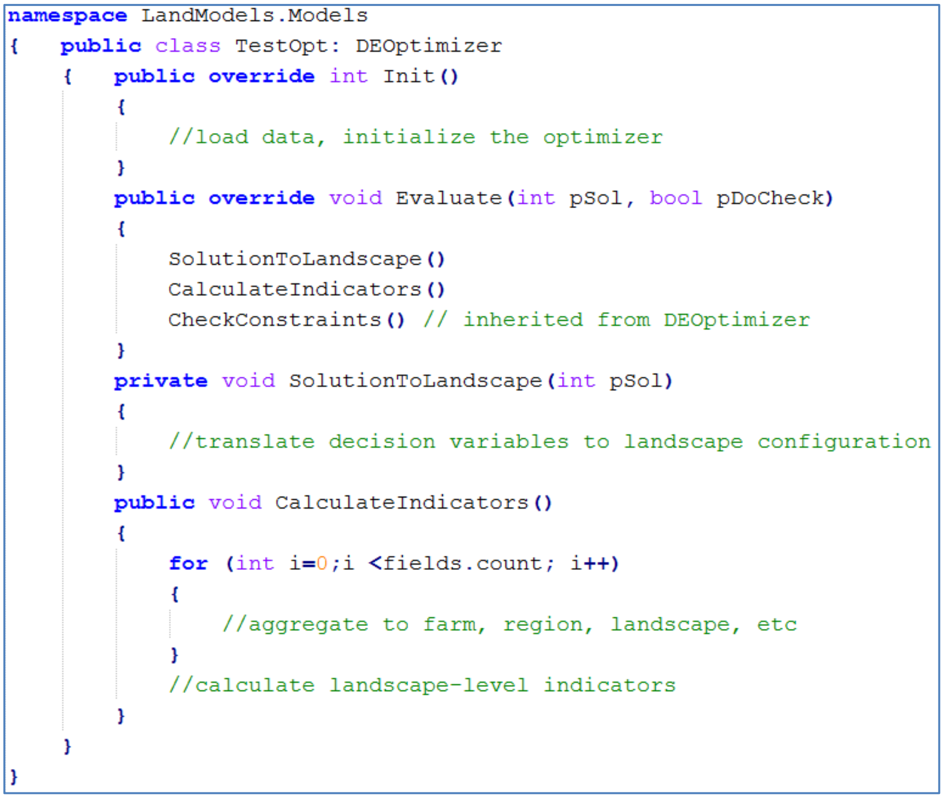
Figure 2. Illustration of a Pareto-based ranking scheme for two objectives U1 and U2 that are maximized. Each circle represents a land-use and management plan. (a) Pareto ranking where non-dominated landscapes are shown with rank 1 (green symbols) and dominated landscapes are shown with ranks 2–4 (yellow symbols). (b) Extended ranking using the extra information of performance of the original land-use and management plan (red square) to assign a superior rank 0 to land-use and management plans performing better than the original for all objectives (blue symbols).

2.2. Application domain: ‘landscape models’

The application domain is designed as a programming interface to access the generic functionalities and methods implemented in the system domain, and create a ‘landscape model’, i.e. a simulated land-use and management scenario for the landscape. A new model in the application domain is implemented in a predefined template and inherits properties (i.e. variables) and methods (i.e. programmed functions that can be reused) from the class DEOptimizer (Figure 3). At least two abstract methods from the DEOptimizer, Init() and Evaluate(), are needed.

Init() first calls the GIS layers to load the landscape shape elements and associated properties from the spatial data files and initializes the values for the landscape elements. These initial values are the case study specific properties of land-use and management. Moreover, when needed, parameters for simulation models are extracted from MS Access/SQLite databases. Then, the number of landscape elements (fields, borders, etc.) to be adjusted during the optimization process is determined, and valid ranges for the identified decision variables are given by the model user. Subsequently, starting values of the objective functions are calculated on the basis of the existing land-use and management.

The Evaluate() method is called by the DEOptimizer (Figure 3) for each generated land-use and management scenario to analyze its performance. First, the land-use and management defined by the decision variables are allocated to the elements in the landscape by the SolutionToLandscape() method. Calculation of indicators takes place in the CalculateIndicators() method, which is set up in such way that indicator calculations can be added or removed from the template, depending on case study requirements. The indicators can be estimated with simple calculations based on the set of production activities (e.g., Groot et al., 2007). Dynamic and spatially explicit models can also be invoked to calculate more complex indicators using, for instance, ecological population dispersal models (Allema et al., 2015) or hydrological models. Lastly, after the indicators have been quantified, the CheckConstraints() method evaluates whether the constraints are met. In the case when constraints are violated the landscape will receive the most inferior rank in the selection process, effectively leading to its removal from the next calculation rounds (Section 2.1).



```
namespace LandModels.Models
{   public class TestOpt: DEOptimizer
    {   public override int Init()
        {
            //load data, initialize the optimizer
        }
        public override void Evaluate(int pSol, bool pDoCheck)
        {
            SolutionToLandscape()
            CalculateIndicators()
            CheckConstraints() // inherited from DEOptimizer
        }
        private void SolutionToLandscape(int pSol)
        {
            //translate decision variables to landscape configuration
        }
        public void CalculateIndicators()
        {
            for (int i=0;i <fields.count; i++)
            {
                //aggregate to farm, region, landscape, etc
            }
            //calculate landscape-level indicators
        }
    }
}
```

Figure 3. Example pseudo-code of a template C# file used in LandscapeIMAGES. The function Init() loads shape and attribute tables, determines the landscape elements to be adjusted during the optimization, gets decision variables and sets their allowed ranges, and calculates the starting values of the objective functions. CalculateIndicators() includes the computation loop for evaluation of generated land-use and management scenarios in each iteration.

3. Graphical user interface

The LI framework includes a graphical user interface that supports the execution of 'landscape model' applications and the visualization of simulation results. It consists of four windows that: (1) shows the original land-use and management configuration and composition across the landscape, which can be edited; (2) presents the performance of the original land-use and management in terms of a set of indicators at farm, region and whole landscape level. This window also allows the selection of constraints and objectives for the optimization; (3) visualizes the progress of iterative improvement of the sets of decision variables during optimization and the final result in terms of the objective functions, and; (4) shows the configuration of user-selected land-use and management scenarios (in window 3) with ranks 0 and 1.

4. Application

To illustrate its functionalities, the LI framework was used to optimize ESs for the land-use in a section of the Hoeksche Waard (Figure 4). The Hoeksche Waard is an agricultural area in the Netherlands, characterized by arable fields amidst an extensive network of dikes, creeks, ditches and field margins (Steingröver et al., 2010). Maintaining the characteristic landscape structures such as polders, dikes and networks of creeks, as well as the quietness and openness of the landscape, conflicts with dominant agricultural development options. The study of land-use and management alternatives was undertaken to support a regional multi-stakeholder process on improving the economic, ecological and social outcomes from the current landscape (Geertsema et al., 2016; Steingröver et al., 2010).

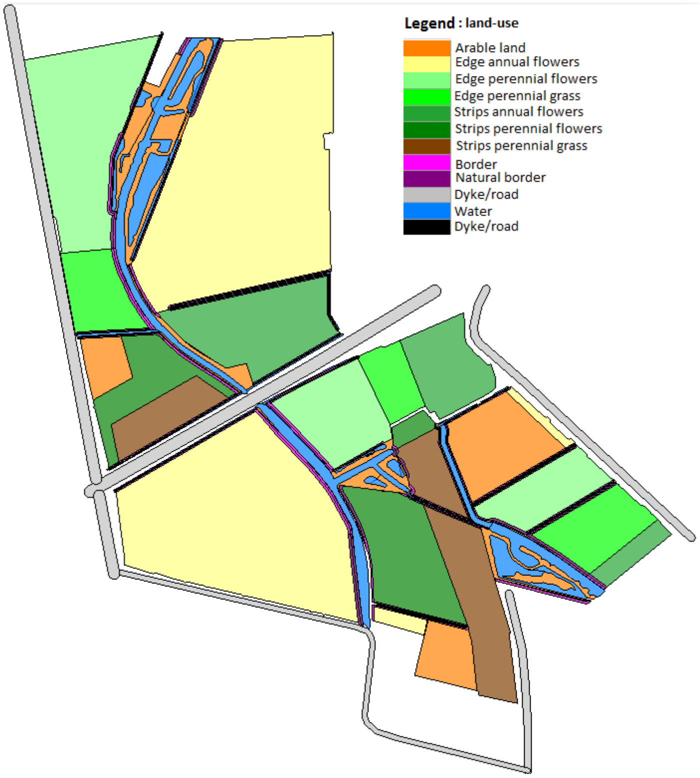


Figure 4. Land-use in a section of the Hoeksche Waard used to illustrate the functionalities of LandscapeIMAGES.

We present two illustrations of LI functionalities based on the Hoeksche Waard case. The first illustration addressed the trade-offs among six indicators related to farming and ecosystem services:

A. Economic returns from farming, calculated as gross margin, i.e. the difference between revenues (from sales and subsidies) and crop cultivation costs.
B. Land-use diversity expressed with the Satoyama index (Kadoya and Washitani, 2011).
C. Biodiversity potential, operationalized as connectivity of potential habitats in the landscape (Urban and Keitt, 1999).
D. Bio-control potential, expressed as the area of flower strips suitable for natural enemies of agricultural pests.
E. Pollution mitigation, calculated as the area of undisturbed creek banks that serve as buffers to pesticide and fertilizer runoff.
F. Landscape quality, operationalized as the visibility of creeks from cycle paths.

The second illustration analyzed the trade-off between private and public landscape performance. Private landscape performance was defined as the market-related benefits for farmers, similar to indicator A mentioned above (see Equation 4). Public landscape performance was measured by aggregating indicators B to F. The aggregation procedure followed Parra-Lopez et al. (2008, 2009) by using weights derived from consultation with experts. Equations 5 describes the weighting procedure:

$$\Delta U_M = \Delta GM - \Delta S \qquad (4)$$

$$\Delta U_{NM} = \sum_{i=1}^{n} w_{Fi} ln \left[\frac{F_i(s)}{F_i(0)}\right] \qquad (5)$$

Where ΔU_M, ΔGM and ΔS denote changes relative to the current land-use scenario in market utility, gross margin and subsidies, respectively, expressed in Euros. ΔU_{NM} is the change in non-market utility that is calculated as the change in performance of indicator $F_i(s)$ of landscape s relative to the current landscape $F_i(0)$, and the relative importance w_{Fi} of the n indicators. In this example n=5, the functions F_1 to F_5 represent indicators B to F. The societal net benefit of a new landscape compared to the current situation is calculated as the sum of ΔU_M and ΔU_{NM}. Dependent on the societal net benefit of a selected land-use and management alternative across the landscape, decisions can be made on the deployment of public policy instruments to stimulate the desired change (Parra-Lopez et al., 2009). Possible policy instruments include taxes, subsidies, technology development, education, etc. A decision to take no action might also be valid if the private and public benefits are both positive under the current land-use and management scenario (Pannell, 2008).

The land-use types allocated to the landscape elements in these examples included arable cropping, semi-natural patches, water bodies, banks, dikes and roads. Additional management decisions related to the types of vegetation on banks and dikes, and the density and composition of flower strips in arable fields.

In Figure 5 the trade-offs of various combinations of ecological service indicators are shown. Figure 5a shows the relation between gross margin and the Satoyama diversity index. The largest values of the Satoyama index could be reached at intermediate levels of gross margin where there is a mixture of land-uses, rather than only highly profitable arable cropping or only semi-natural habitats with low economic returns. Figure 5b shows the strong trade-off between connectivity and economic profitability at the landscape level. Similarly, we found a trade-off between the market benefits and the non-market benefits derived from the landscape (Figure 5c). The maps (Figures 5d, 5e and 5f) demonstrate the configuration and composition of land-use across the landscape that is associated with performance of specific indicators, and provide insight into the changes compared to the original landscape (Figure 4).

Agricultural landscape managers and policy makers at various scales can benefit from the analysis and visualization tools supported by the LI framework. Similar frameworks have been developed for watershed planning and management (Martin et al., 2016). Further development of these frameworks should explicitly address system robustness and uncertainty, as well as system transitions (Crespo et al., 2010; Holzkämper et al., 2015; Singh et al., 2015). As a future technological development for the framework, we envisage implementation of a standard model interface such as the Open Modeling Interface (Knapen et al., 2009) for easier coupling with other farm, landscape, or watershed assessment models. We also foresee migration of the framework to a platform independent version.

The generic structure, the object-oriented modeling approach, the availability of model templates and the use of standardized file and GIS formats allow relatively rapid development of new modules for new case studies in different landscape planning settings. However, the model will always require adjustments to pre-process the GIS maps, fill the model databases and develop the indicators that are new to the framework. This calls for software engineering and database management skills.

This type of model-based support can be useful in various types of land-use management and planning activities. These range from long-term strategic planning over a time-span of several years, to yearly tactical planning and short-term operational planning to schedule activities based on the tactical plan spanning days or weeks (Huirne, 1990). LI is particularly useful for strategic planning as it relates to land-use change and is expected to have less utility for tactical and operational landscape management.

5. Conclusions

We presented and demonstrated the LI modeling framework, which is designed for multi-objective optimization of agricultural land-use and management planning across landscapes. The objectives used are indicators of ecosystem service provisioning, and can range from economic and social performance of farms and landscapes to ecological processes involving, for instance, biocontrol, strengthening of biodiversity and pollution mitigation. LI can be used to analyze trade-offs and synergies among selected indicators. Maps of simulated land-use and management scenarios across landscapes are generated to visualize the type and location of land-use adjustments that would improve the performance of the selected indicators. Clarifying trade-offs and visualizing land-use and management changes can provide insights into the consequences of different stakeholders' priorities and choices, thereby serving as discussion support for participatory landscape planning and negotiation sessions.

The generic design of the LI framework means that it is accessible and useful for researchers and developers from various scientific domains, such as hydrology, land-use change and agroecology. LI is currently applied in various projects aimed at strengthening multifunctionality of agriculture, biodiversity and ecosystem services in landscapes in Asia, Africa, Latin America and Europe.

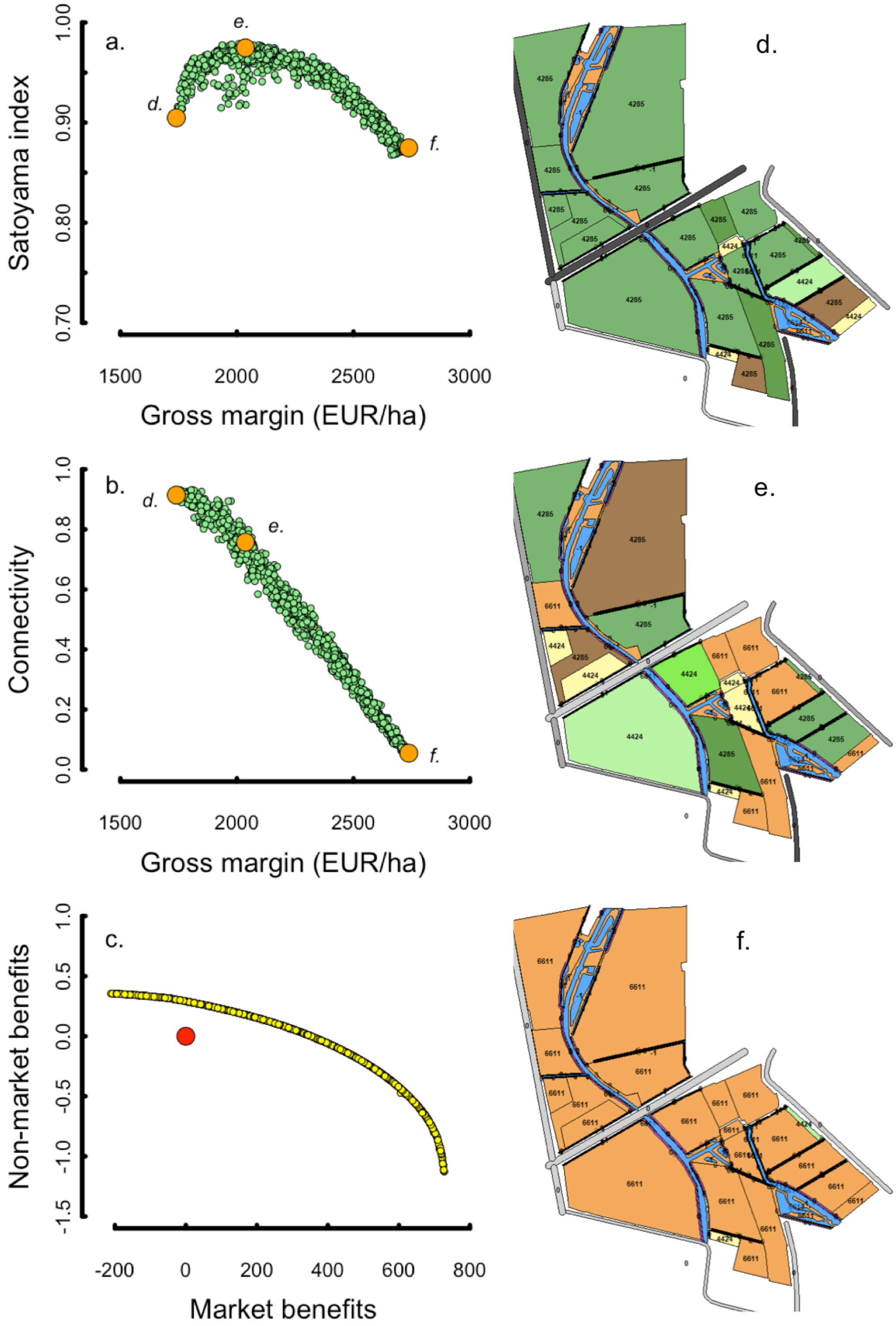


Figure 5. Relations between (a.) gross margin and Satoyama index; (b.) gross margin and habitat connectivity; and (c.) market and non-market benefits, after 1000 iterations of Pareto-based multi-objective optimization. In (a.) and (b.) the orange symbols accompanied by the italicized

letters highlight selected land-use scenarios for which the corresponding maps are displayed in figures (d.), (e.) and (f.). The numbers displayed in each of the polygons on the maps are gross margins (€ ha^{-1}). The red symbol in (c.) denotes the original landscape.

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