Landscape Prototyping: towards an integrative approach for the design and analysis of multifunctional agricultural landscapes

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Abstract

Multifunctionality is seen as one of the solutions to society's demand for new functions in the rural areas and the problems with the unsustainability of the agricultural sector in the European Union. In contrast to the traditional functions of income, labor and food production these new functions can not be provided by a single field or a farm. Planning and production of functions like: Nature Conservation, environment and landscape esthetics can only be achieved when the landscape is considered as a whole.
We present an outline of a methodology based on concepts and insights from production ecology and landscape ecology, that should enable us to explore the opportunities for multifunctional agriculture, balancing objectives at three spatial scales: field, farm and regional level. The focus of this paper is on the integration of the agricultural production and nature conservation. However, the methodology aims to be easily adaptable for other services.
In this paper the concepts of explorative design and habitat networks are explained and integrated to design landscape prototypes. Landscape Prototypes are spatial explicit images of multifunctional agricultural landscapes based on scientific insights and indicating quantitatively the services provided within these virtual landscapes. An important output of the approach are trade-off curves between the different services provided by the landscape. We discuss the implications of our approach for landscape ecological and agronomic research which is on-going in our research program.

Keywords:
Multifunctional Agriculture, Design, Habitat Networks, Linear Programming, Biodiversity

Introduction

Multifunctionality is seen as one of the solutions to society's demand for new functions in the rural areas and the problems with the unsustainability of the agricultural sector in the European Union (Vos and Meekes 1999, OECD 2000, EC 2000).

In answer to this demand agriculture can provide different kind of services in addition to the traditional functions of the production of food, fibers, labor and income. Farmers and agricultural production systems can contribute to a healthy environment, biodiversity and landscape esthetics (Vereijken 1998). In contrast to the traditional products of agriculture, these additional services cannot be provided at a single field or farm, but need to be considered on a landscape level.

To restore the natural, environmental and esthetic values in the agricultural landscape, the landscape as a whole needs to be considered. For example it has been shown in an evaluation study that biodiversity protection on single farms does not enhance the biodiversity (Kleijn et al. 2001), but modeling studies show that the spatial clustering of these protective measures do (Geertsema 2002). Water levels, tables

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and quality can only be managed at a regional (catchment or polder) scale (Barendregt et al., 1993). Spatial coherence is one of three factors determining the quality of landscape experience in agricultural area's (Hendriks et al. 2000). Therefore policy makers, planners and individual farmers interested in the multifunctional concept have to consider the land-use on field and farm level within the total spatial configuration of the landscape.

In this paper we present a framework with which we aim to explore the opportunities for multifunctional agriculture by balancing objectives at three different spatial scales: the field level, the farm level and the landscape level. The framework is based on the concepts of explorative design and ecological networks and focuses on objectives related to agricultural production and nature conservation. The methodology is aimed at easy adaptability for other services. By presenting the conceptual basis, as yet without proof-of-concept, we aim to stimulate thinking on methodologies to bridge the agriculture-nature divide that are urgently needed if we are to support discussions on multifunctional agricultural land use.

Explorative Design

The explorative design methodology is a modeling approach to identify and engineer future-oriented land use systems based on how crops use resources and how a farmer may manage production systems (Dogliotti 2003). In this approach an optimization technique, usually linear programming, is used to select and quantify the 'optimal' combination of land use activities for a certain area, matching a set of predefined land use objectives and constraints (Figure 1).

The explorative design methodology starts by generating a large number of alternative land use activities at the field scale in a systematic manner. Each of these land use activities is then quantified in terms of input-output coefficients. An input-output coefficient is the quantitative description of the relation between the necessary input for the land use activity, for example kg fertilizer-N, kg water, h labor per ha, and the expected outputs, kg product, N-emission per ha (Ittersum and Rabbinge 1997) and has to match the specific physical conditions of the area. Alternative production methods can be used to cultivate the same crop, each production method resulting in a different land use activity, with different input-output coefficients. Through the input-output coefficients, land use systems can be evaluated in terms of objectives of land use. In addition, input-output coefficients define the demand of land use systems on resources.

Land use activities may be derived from current agricultural practice, but new activities can be defined using expert knowledge or models. In this way innovative land use systems can be developed and evaluated. Evaluation may take place at the farm or regional scales, depending on the purpose of study, and often linear programming has been employed to identify optimal land use patterns. An important output of the approach has been to benchmark discussions on various options of land use by calculation of trade-off curves. Technically, these trade-off curves are created by systematically varying the different objectives for the study area and re-running the linear programming model that is used to select optimal combinations of land use for the farm or region. Started in the Wageningen group (De Wit et al., 1988), the approach has meanwhile been taken up and extended for conservation issues by Zander (2003) and co-workers.

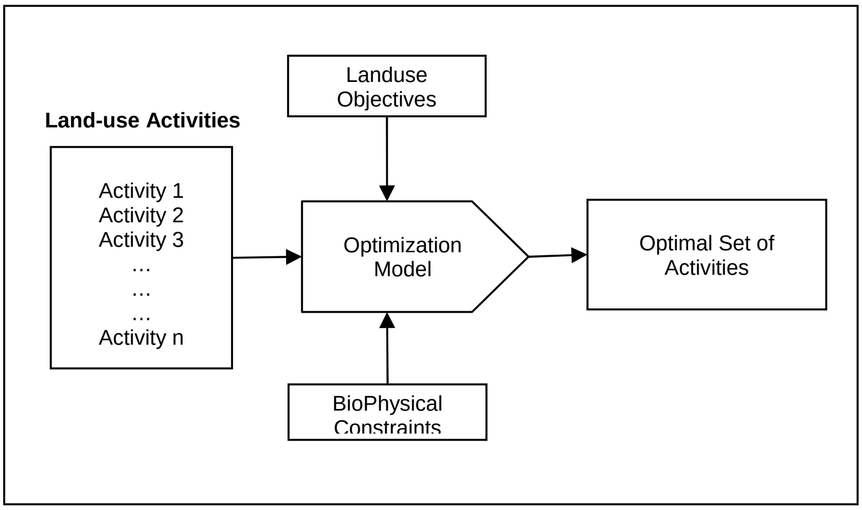

Figure 1: Schematic representation of the Explorative Design Methodology

Habitat Networks

A collection of suitable habitat patches embedded in a matrix of non-habitat linked by the movement species dispersal is called a habitat network (Opdam 2003). These habitat networks are an important concept for species conservation in a fragmented landscape. The basic notion of this concept is that the population can survive through time within the network, due to the process of dispersal. The habitat network is effective only if the habitat quality, as well as the spatial arrangement of the patches and the resistance of the landscape matrix allow the persistence of the target species.

Rules for the design of habitat networks are difficult to establish. Measuring the population dynamics in the field is very time consuming. Further more every studied landscape will provide only a single observation for the establishment of generic rules for habitat network design (Vos et al. 2001). A better way to develop such rules is the usage of spatial population dynamic models (Opdam 2002). Spatial population dynamic models are computer models that calculate the population dynamic behavior of a species in a virtual landscape by simulating the key species characteristics. To obtain reliable results these models should be calibrated using field observations. By systematically altering the network configurations, the relation between the population dynamic behavior of the model and network configuration can be studied. Examples of such an approach are Verboom et al. (2001) and Frank and Wissel (1998). In literature a wide variety of spatial population dynamic models is available (Czárán 1998), the best models to evaluate the configuration of habitats are spatial explicit individual based models (Wiegand et al.1999).

Synthesis

To integrate the concept of habitat networks into the explorative design methodology two important steps need to be taken.

1. The explorative design methodology has to be made spatially explicit.
2. And the relation between land use activities and the survival of the population has to be expressed in input-output coefficients.

Making the explorative design methodology spatially explicit can be realized relatively simply by linking the optimization model to a GIS environment. By introducing every landscape element in the GIS environment as a separate variable in an optimization model the land-use type for each of the landscape elements can be determined. Because the locations of all the land elements are known, the locations all land-use types are known.

To describe the relation between land use types and population survival in input-output coefficients is more difficult. In general the land use activities in a landscape element will determine the habitat suitability for the species. However as explained above the number of individuals inhabiting that landscape element is not only depending it's own the quality, but also depending on the spatial arrangement and quality of the other habitat patches and the characteristics of the surrounding landscape matrix. Therefore the contribution of a land use activity to the survival probability of a species is strongly non-linear and cannot be expressed in simple input-output coefficients.

In landscape ecological literature heuristic optimization algorithms are used to solve this problem. In these algorithms a spatial rules or simple population dynamic models are used to evaluate the complete habitat configuration for each optimization step. Examples can be found in Cabaza 2003 and Groeneveld 2003 both founding their evaluation rules on the Incidence Function model (Hanski 1994). In this model the chance of survival for a species in the habitat network is determined based on the extinction and colonization chances of the populations in the network. In the model it is assumed that each of these populations is semi isolated having its own internal independent population dynamics, interaction between populations only consists of relatively rare colonization events.

In agricultural landscapes semi-isolated populations are difficult to identify. In these landscapes small landscape elements like single trees, hedgerows, field margins and canals are the main carriers of biodiversity (Kleijn 1997, Grashof-Bokdam & van LangeVelde 2004). Many of these elements will be too small to support a population in isolation. However several small landscape elements elements located close to each other might support a population by constantly exchanging individuals. The population dynamics of such elements are not independent at all. Other elements, like linear habitat patches may be so elongated that they contain several semi isolated populations. To evaluate these type of habitat networks more mechanistic are needed, for example spatial explicit individual based models. However the usage of this type of models in an iterative process of network design will be far to complex and time consuming.

Therefore in this paper we propose a different approach, combining an optimization model and a network generator. The network generator will be used to generate a large number of habitat networks differing in habitat configuration and ecological value. The optimization model will be used to select one of the habitat networks and to optimize this network for agricultural production. Which of the generated habitat networks will be selected and how this network is optimized depends on the predefined land use objectives. The selected habitat network will be used as a constraint for the selection of appropriate land-use activities. In the section below this approach will be explained in larger detail.

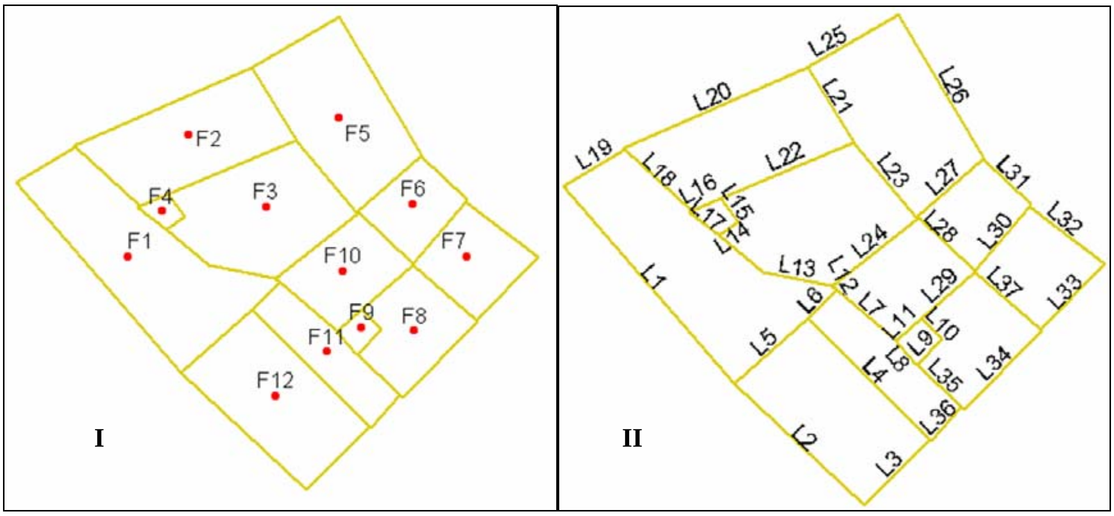

Figure 2: Conceptual Landscape Model: I Polygons representing agricultural fields, II Lines representing linear elements like hedgerows, field margins or canals.

Landscape Prototyping

The landscape prototyping methodology consists of three components:

1. A GIS environment
2. A Network Generator
3. And an Optimization Model

The GIS Environment

In agricultural areas the dominant landscape features consist of production fields and linear elements like hedgerows, canals and field margins. Therefore we have conceptualized the landscape in the GIS environment by polygons and lines, the polygons representing the fields (F), the lines representing the linear landscape elements (L) (Figure 2). In our conceptual model of the landscape 3 spatial levels are recognized (Figure 5):

1. The Field level consisting of the individual fields and linear elements.
2. The Farm level consisting of the agglomerations of those landscape elements belonging to the same farm.
3. The Landscape level consisting of all elements in the landscape.

Within each of the landscape elements different land use activities occur. A land use activity can be a particular crop rotation or a meadow, but also a windbreak, a hedgerow or a channel. Each of the land use activities can be described in terms of habitat quality for a particular species. We assume that all land use activities can be divided into a limited number of habitat quality categories. In our conceptual landscape model a land use activity can have an effect, positive or negative, on the habitat quality of neighboring landscape elements. For example the application of fertilizer can have a negative effect for the habitat quality for certain plants in a neighboring hedgerows, on the other hand the growth of a wheat crop can have a positive effect on the habitat quality of the same hedgerow for mice. This conceptual landscape forms the basis for the design and optimization of multifunctional landscapes.

The Network Generator

The concept for the development of a network generator can be found in production ecological literature. In Dogliotti et al. 2003b, it is described how a software tool 'ROTAT' is developed to generate alternative crop rotations based on agronomic criteria. The program combines crops from a predefined list to generate all possible rotations. The full factorial number of possible combinations of crops is limited by a number of filters controlled by the user. These filters are designed to eliminate crop successions that are agronomical unfeasible or for farm-specific reasons not practical or desirable. Selection criteria for the filters are based on timing, sequence and frequency constraints for crop cultivation techniques and farm-specific feasibility and applicability. These filters represent expert knowledge in a quantitative and explicit way.

Habitat networks can be generated fixing the topology of a landscape and by systematically varying the habitat quality of the different landscape elements. Ecological rules can be used to filter all unfeasible or undesirable combinations. For ecological networks these criteria could be expressed in total habitat area constraints, connectivity constraints, patch size constraints, habitat quality constraints, etc. Using a network generator in this way a large set of habitat networks can be generated varying in ecological value and habitat configuration (Figure 4). The generated network configurations are input for the optimization model.

However the proposed network generator can produce a very large number of habitat networks. For each landscape element, habitat class or land use activity added to the generator, the number of possible combinations increases manifold. Therefore it is important that not all but only a representative selection habitat networks will be generated.

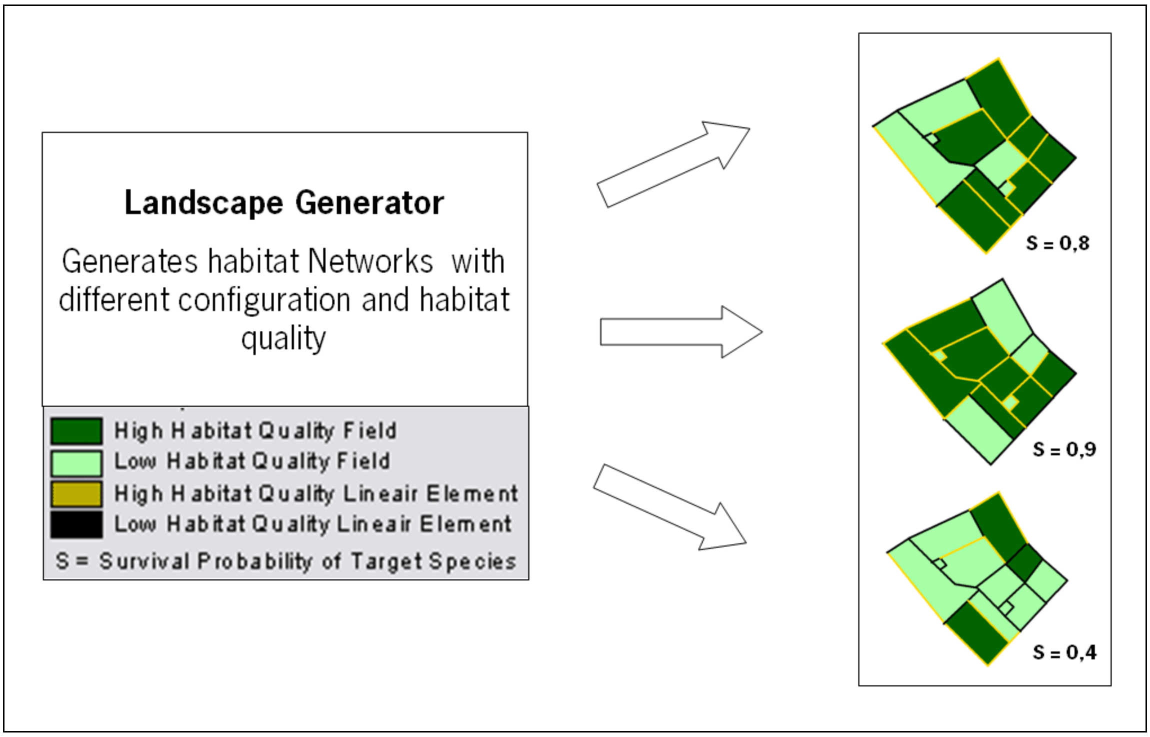

Figure 3: In step 1 a network generator is used to configure all possible network configurations for predefined set of parameters

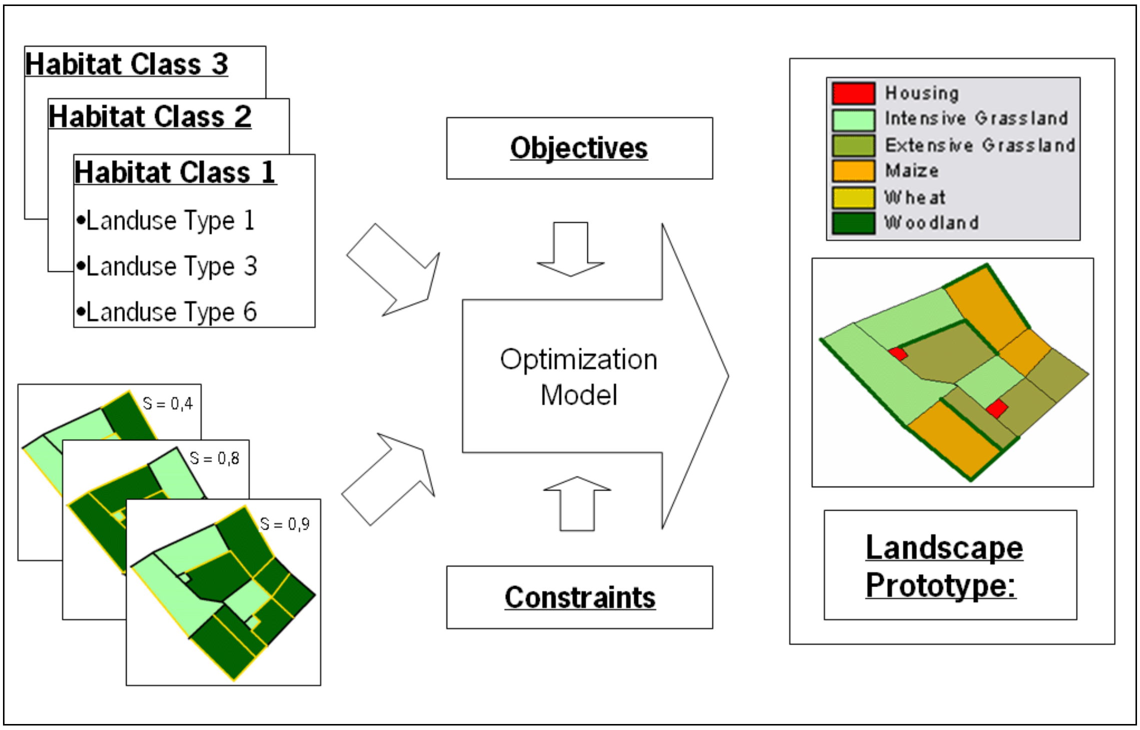

Figure 4: In step 2 an optimization algorithm is used to select one of the habitat networks and to optimize the agricultural activities. Which network is selected and how the agricutural production is optimized is depending on predefined opjectives and constraints

Optimization Model

In the second step of the landscape prototyping methodology the optimization algorithm is used to select one of the habitat networks and to optimize the land use within this network for agricultural production (Figure 4). The habitat network is used as a constraint for the optimization of the land use. All the land use activities are divided in a limited set of habitat classes. Within each of the habitat classes the land use is optimized. Which of the habitat networks is selected and how the production is optimized depends on the predefined objectives and constraints

In the optimization model four types of constraints will be formulated: Landscape Constraints, Adjacency constraints, Farm constraints and Field constraints (Figure 5).

- Landscape constraints are constraints at landscape level, for example the minimal ecological value of a landscape.
- Adjacency constraints are constraints on the land use in the neighboring landscape element, for example on the usage of pesticides or the cultivation of a certain crop
- Farm constraints are constraints at farm level, for example the minimum income of a farm or the maximum labor use.
- Field constraints are constraints at field level, for example the minimum habitat quality of a land use activity in a specific landscape element.

The basis for such a model can be derived from existing farm optimization models (ten Berge et al. 2001, van der Ven et al 2003, Dogliotti 2003a).

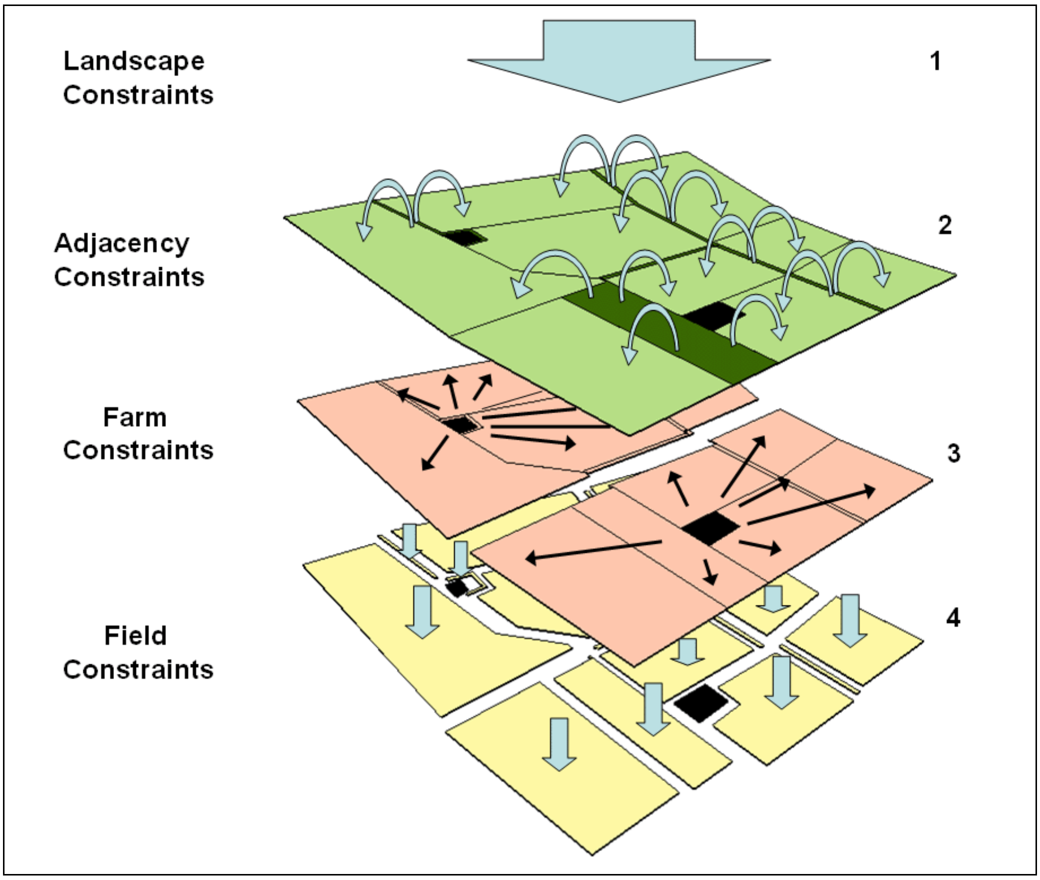

Figure 5: In the optimization model objectives can different type of constraint will be formulated, 1 Landscape constraints, 2 Adjacency constraints, 3 Farm constraints and 4 Field constraints

Expected Results and Perspectives

The expected results of the methodology are landscape prototypes and trade-off curves (Figure 6). Landscape Prototypes are spatial explicit images of multifunctional agricultural landscapes based on scientific insights. These images can be used to facilitate the discussion about multifunctional agriculture by visualizing and illustrating different types of multifunctional landscapes. Because landscape prototypes are based on landscape ecological and production ecological knowledge, these illustrations are more then an artistic impression of the landscape.

Trade-off curves can be created by systematically varying the different land use objectives and re-running the optimization model. In this way the contours of the window of opportunities for multifunctional agriculture can be revealed.

In this paper we have focused on combining the services of agricultural production and nature conservation. Multifunctional agriculture can provide more services like landscape esthetics or environmental functions. Many of these functions also have a spatial component. These functions can also be included in the landscape prototyping methodology, by using insights from other scientific disciplines to adapt the filters in the network generator or the constraints in the optimization model. Therefore we believe that landscape prototyping can be a promising approach to study multifunctionality.

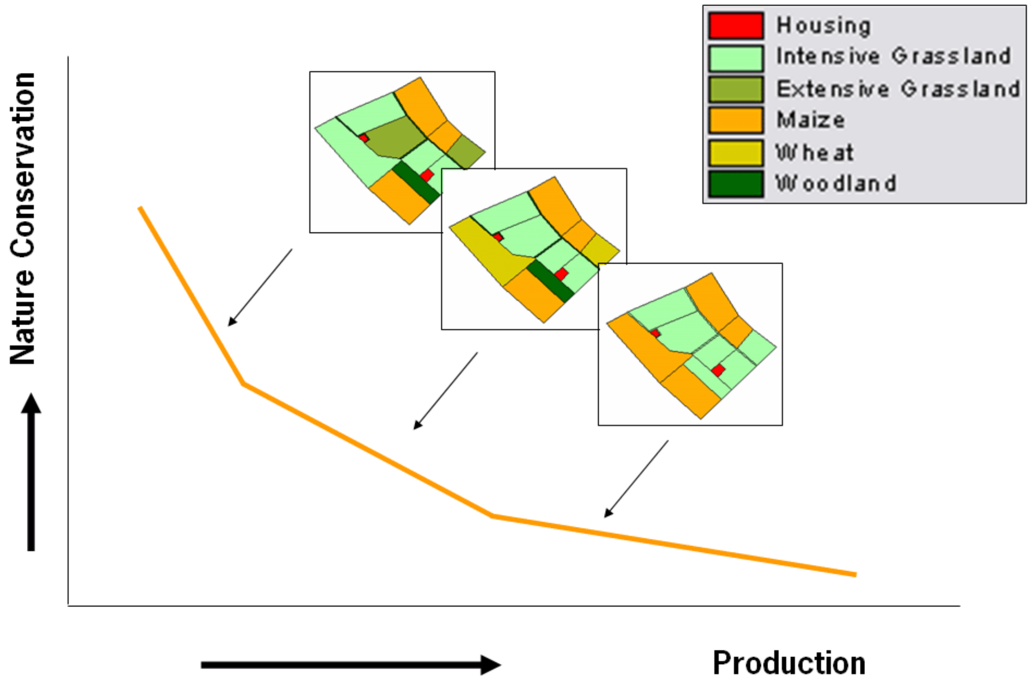

Figure 6: Imaginary trade-off between production and nature along with selected landscape prototypes. The figure is meant to illustrate the approach proposed in the paper

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