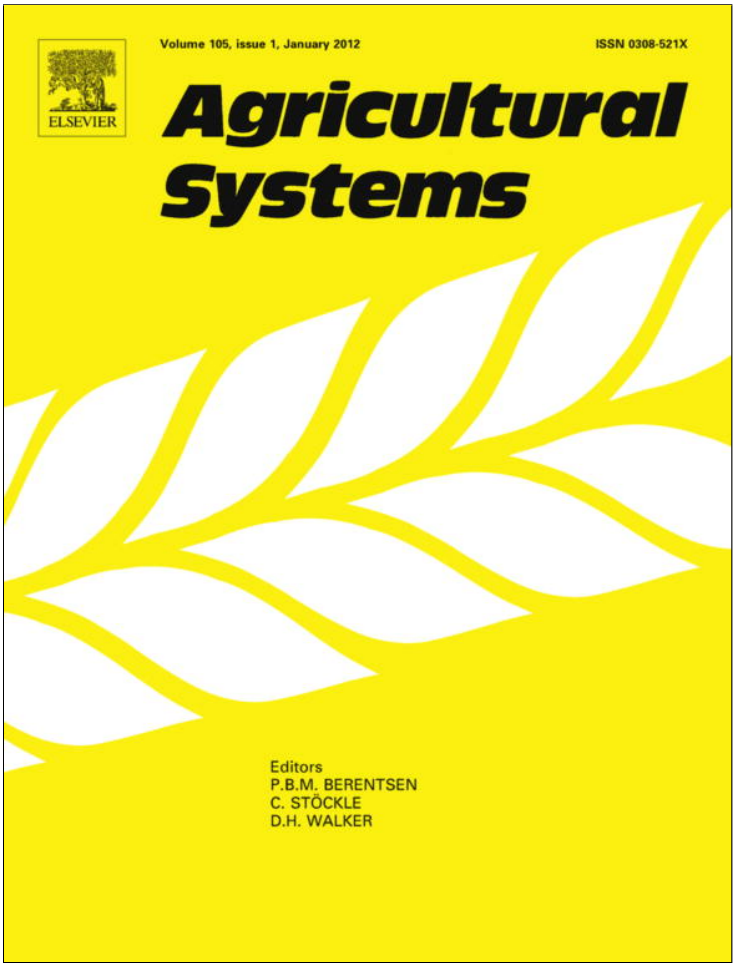
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Multi-objective optimization and design of farming systems

Jeroen C.J. Groot *, Gerard J.M. Oomen, Walter A.H. Rossing

Wageningen Centre for Agro-ecology and Systems Analysis (WaCASA), Organic Farming Systems Group, Wageningen University and Research Centre, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands

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ABSTRACT

Reconfiguration of farming systems to reach various productive and environmental objectives while meeting farm and policy constraints is complicated by the large array of farm components involved, and the multitude of interrelations among these components. This hampers the evaluation of relations between various farm performance indicators and of consequences of adjustments in farm management. Here we present the FarmDESIGN model, which has been developed to overcome these limitations by coupling a bio-economical farm model that evaluates the productive, economic and environmental farm performance, to a multi-objective optimization algorithm that generates a large set of Pareto-optimal alternative farm configurations. The model was implemented for a 96 ha mixed organic farm in the Netherlands that represents an example with relevant complexity, comprising various crop rotations, permanent grasslands and dairy cattle. Inputs were derived from a number of talks with the farmers and from literature. After design-, output- and end-user validation the optimization module of the model was used to explore consequences of reconfiguration. The optimization aimed to maximize the operating profit and organic matter balance, and to minimize the labor requirement and soil nitrogen losses. The model outcomes showed that trade-offs existed among various objectives, and at the same time identified a collection of alternative farm configurations that performed better for all four objectives when compared to the original farm. Relatively small modifications in the farm configuration resulted in considerable improvement of farm performance. This modeling study demonstrated the usefulness of multi-objective optimization in the design of mixed farming systems; the potential of the model to support the learning and decision-making processes of farmers and advisers is discussed.

1. Introduction

Agricultural systems continue to put large pressures on the environment (MA, 2005; Pretty, 2008; Kiers et al., 2008; Place and Mitloehner, 2010). In arable crop production, intensification of cultivation practices in monocultures to achieve higher yields results in large use of pesticides and fertilizers, which can be lost from the farming system and pollute water, air and natural ecosystems (Tilman, 1999). Intensive cropping systems cause depletion of organic matter stocks in agricultural soils and put pressure on soil structure, which leads to decreasing soil fertility, water holding capacity and resistance to erosion and compaction. In intensive livestock production systems nutrient concentration caused by feed and fertilizer imports and the use of antibiotics and hormones can cause environmental pollution, whereas in less input-dependent pastoral systems overgrazing can lead to degradation of rangelands and semi-natural vegetation and can eventually cause invasions of unpalatable shrubs and desertification (Steinfeld et al., 2006; Herrero et al., 2009).

Naylor et al. (2005) identified reconnection of livestock to the land, either physically or through policies, as a crucial development to mitigate the disrupting effects of the externalization of negative impacts by agriculture. Mixed farming systems allow for physical reconnection of livestock to the land, and therefore offer a promising alternative archetype to the ongoing development of industrialization of crop and animal production systems (Herrero et al., 2010). In mixed crop-livestock systems, animals can have multiple purposes besides the primary production of milk, meat, eggs and wool. Animals can serve as a capital stock, contribute to nutrient cycling by their manure production and large animals can provide draught power. In well-managed mixed farming systems with limited external inputs, balanced rotations and appropriate stocking rates, nutrient cycling and organic matter use can be improved to avoid soil mining or pollution and to enhance the organic matter content and soil structure (Oomen et al., 1998; Schiere et al., 2002; Lantinga et al., 2004; Watson et al., 2005; Petersen et al., 2007; Russelle et al., 2007; Hendrickson et al., 2008). This holds large promises for the development of sustainable agroecosystems (Wilkins, 2008; Hilimire, 2011).

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* Corresponding author. Address: Wageningen Centre for Agro-ecology and Systems Analysis (WaCASA), Organic Farming Systems Group, P.O. Box 563, 6700 AN Wageningen, The Netherlands. Tel.: +31 317 485924; fax: +31 317 481203.

E-mail address: jeroen.groot@wur.nl (J.C.J. Groot).

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The planning of mixed farming systems with an array of crops, various animal types and a diverse range of other resources is complicated, since it involves many management decisions on resource allocation (Russelle et al., 2007). These choices and their resulting outcomes are subject to a large range of objectives and constraints. The objectives include the need for sufficient financial returns to maintain the livelihood of farmers and farm workers, and environmental goals to safeguard the sustainability of the system, for instance by increasing the organic matter build-up in the soil and reducing nutrient losses. The constraints originate from biophysical conditions that can restrict the possibilities for allocating crops and rotations or from agronomic knowledge of acceptable crop sequences and cultivation practices. Moreover, the nutritional needs of animals should be balanced with feed supply and the labor and water requirement should be matched with the availability of these resources. In organic farming systems additional constraints ensue from organic regulations, such as a maximum manure application rate, a minimum feed self-supply rate and a minimum rotation length.

Model-based support can be useful in various hierarchically structured planning windows. 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, for a number of days or weeks (Huirne, 1990). Recently, various tools have been developed and applied for integrated farming system analysis (Modin-Edman et al., 2007; Bechini and Stöckle, 2007; Millar et al., 2009; Küstermann et al., 2010; Andrieu and Nogueira, 2010; Le Gal et al., 2010; Del Prado et al., 2011) and for the exploration of strategic improvements in farming systems (Dogliotti et al., 2005; Groot et al., 2007; Tittonell et al., 2007a, 2007b; Vayssières et al., 2010). However, methodologies that enable tactical planning, and that can provide rapid insight into the consequences of large ranges of farm reconfiguration options would be very helpful to inform the planning process of farmers and farm advisors. Ideally, this planning process would take the shape of an iterative innovation and learning cycle. An integrative modeling methodology to support this process would enable the analysis of synergies and trade-offs among different objectives (cf. Groot et al., 2010). Rapid inspection of the farm configurations (crops areas, animal numbers, manure application, etc.) associated with different performance levels should be possible. Recently developed easy-to-use visualization tools can play an important role (Kollat and Reed, 2007; Castelletti et al., 2010). Pareto-based multi-objective optimization methods are well-suited to carry out such explorations of trade-offs and synergies (Groot and Rossing, 2011).

In this paper we present the FarmDESIGN tool, which supports evaluation and re-design of mixed farming systems in tactical planning processes. In Section 2 we describe the modeling tool, which consists of a database, a static model to calculate the farm performance and a multi-objective optimization algorithm. In Section 3 a case study farm is introduced and the results of the optimization are presented in the Results section (Section 4). This is followed by a discussion and conclusions (Section 5).

2. Model description

2.1. Farm database

The input database contains data that describe characteristics of the various resources that can be found on the farm. An overview of the farm components that are included in the input database is provided in Fig. 1. Here we list the types of data entities and the main categories of data:

- Biophysical environment: soil characteristics and chemical composition, climate, deposition, non-symbiotic fixation and potential erosion rate.
- Socio-economic setting: currency, interest rates, prices of labor, general costs, available labor, fixed labor requirements for farm and herd management.
- Crops: agronomy, subsidies, cultivation costs and labor requirement. Each crop can have one or more products.
- Crop products: production per ha, destination (used on-farm e.g. as animal feed, bedding material, green manure, fire-wood, for home consumption), chemical composition, feed value and product price.
- Rotations: per rotation a list of crops and their area. More than one rotation can be defined and crops can also be used in more than one rotation.
- Crop groups: a list of crops belonging to a group on the basis of similar cultivation practices (e.g., root crops) or same plant family (e.g., Allium family).
- Animals: management, labor requirements, weight, production and feed requirements.
- Animal products: destination (use on farm as animal feed or for home consumption), chemical composition, feed value and product price.
- On farm produced manures: composition, nitrogen losses and degradation parameters. The amount of on-farm produced manures is calculated by the model, see Section 2.2.5.
- Fertilizers and imported manures: amount purchased and composition.
- Buildings and equipment: fixed costs for interest and depreciation, variable costs for operation.

A detailed overview of data required for the model that are stored in the database is presented in Appendix A.

2.2. Farm model

A farm is conceived as a management unit consisting of a large array of interrelated components of various types, as listed above for the farm database and displayed in Fig. 1. A static farm balance model is used to calculate flows of organic matter, carbon, nitrogen, phosphorus and potassium to, through and from a farm, the resulting material balances, the feed balance, the amount and composition of manure, labor balance and economic results on an annual basis. We assume a steady state situation on the farm, so that no net changes in stocks and herd occur. Imports or exports of products are calculated from the difference between production and on-farm use. For product use the amounts allocated to different destinations are specified for all crop and animal products. Economic calculations allow the determination of crop and animal margins, fixed costs, operating profit and return to labor.

The farm components represent production activities defined by inputs and outputs. The output variable yield and required inputs are specified in advance in a target-oriented fashion (cf. van Ittersum and Rabbinge, 1997). Thus, crop yields do not respond dynamically to fertilizer levels or other management operations, but required nutrients are calculated from the target crop yields and nutrient concentrations in products. Nutrient inputs in fertilizers, deposition and fixation are compared with nutrient requirements in balances at farm level. Likewise, the production level of the animals is specified in terms of the mass of products (milk, meat, wool, eggs), which results in a set of requirements for energy and protein and possibly other ration components. These requirements are compared with the various dietary components in the feed that is supplied to the animals in a feed balance. Thus, similar to crop yields, animal yields do not respond dynamically to

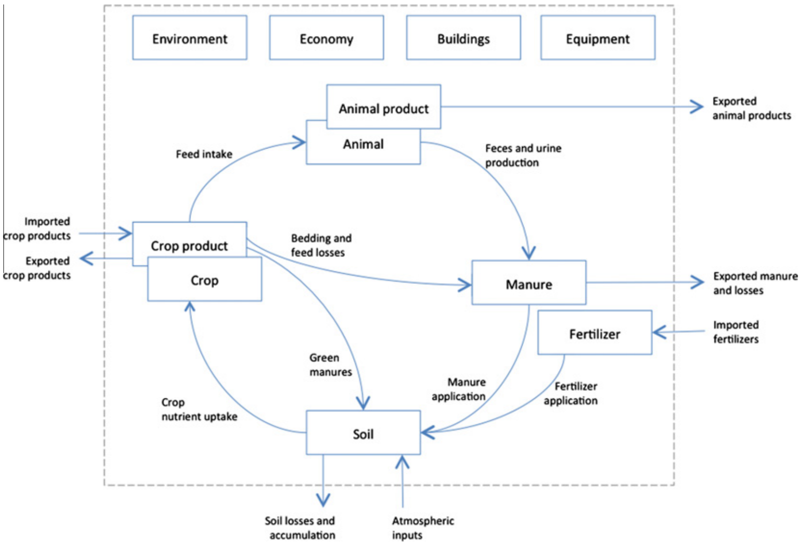

Fig. 1. Schematic representation of the farm model and data within FarmDESIGN. The boxes indicate farm components included as entities in the model, the arrows represent material flows quantified by the model. The dashed lines denote the farming system boundary with the external environment.

management. The generic definition of animal entities allows specifying various types of animals (e.g., calf, yearling, milk cow, dry cow, steer, oxen, horse, sheep, chicken), dependent on the livestock present on the farm and the structure of the herd, provided that their requirements can be expressed in the selected units for energy, protein, structure (if applicable) and saturation.

2.2.1. Crop areas, groups and rotations

From the areas of the crops in each rotation the total area and frequency of the crops on the whole farm and in the crop groups is calculated. For agronomic reasons it may be desirable to limit the frequency of occurrence of the crop group on the farm, for instance to avoid pests and diseases that are associated with a plant family, or to avoid soil structure deterioration due to frequent harvesting of root crops. The frequency of cultivation of crops belonging to a group can be used as a constraint in the optimization.

2.2.2. Feed balance

Feed balances are calculated for energy, protein, structure and the degree of saturation of the intake capacity by subtracting the requirements from the amounts allocated in crop products. In these calculations, the feed intake level and the energy and protein concentration can be expressed in any of the available feed evaluation systems. Different contributions of feedstuffs to saturation can be specified. We assume substitution of roughage by concentrate dependent on the saturation factor of individual feeds. To accommodate large differences in ration composition that can occur within a year, two periods can be distinguished, for instance a grazing and a non-grazing period in temperate regions, or a dry and a wet season in semi-arid regions. For temperate regions the grazing period occurs during the growing season in spring and summer when enough herbage is produced outdoors to allow grazing, when needed supplemented with other roughages and concentrates. The non-grazing period is during autumn and winter when animals spend most of the time in the stable and are fed mainly conserved roughages and concentrates. Per animal type the number of days spent grazing is specified. Separate feed balances are calculated for the two periods, aggregated at herd level.

The animal requirements for energy and protein are related to milk production, metabolic weight and growth using coefficients that are stored as parameters in the database. The maximum feed intake by the animals is related to the body weight. The requirement for structural material in the diet for ruminants (i.e., fibers that stimulate rumen function) is related to feed intake. The feed value of crop products is specified by parameters that quantify the energy and protein contents, the structure value and the contribution to saturation of the feed intake capacity. In this study we have used the Dutch VEM and DVE systems (Van Es, 1975; Tamminga et al., 1994).

2.2.3. Nutrient flows and cycles

Based on the productivity of the crops, the destinations of crop and animal products (and imports and exports, see Section 2.2), the animal feed balance (Section 2.2.2) and the calculations of manure and organic matter turnover (see below in Sections 2.2.4 and 2.2.5) the flows of carbon and nutrients (N, P and K) on the farm are quantified. As an illustration, Fig. 2 gives an overview of the flows in the nitrogen cycle on the farm. Soil N loss, is the amount of nitrogen that can be potentially lost by leaching or denitrification, is calculated from the difference between inputs to and known outputs of the soil component, and thus forms the balancing item.

2.2.4. Organic matter balance

The organic matter balance is calculated as the difference between organic matter (OM) accumulation and OM loss. The accumulation originates from roots and stubble that remain on the field after harvest, green manures that are grown as a source of OM and ploughed under before growing a next crop, feed losses that are dependent on the feeding system and type of feed supplied, and manure either produced on-farm due to excretion by the animals or imported from an external source. Part of the manure is degraded in the year of excretion and other losses of OM occur through breakdown of active organic matter in the soil and erosion of soil.

Rates of organic matter degradation are affected by the following environmental variables, summarized in an empirical relation (Eq. (1)).

- Soil moisture availability quantified as the number of days per year with a soil pF-value lower than 3.5 (W; days). It is assumed that when moisture is insufficient no OM breakdown occurs, due to reductions in water transport, in solute diffusion and in motility and survival of microorganisms (Rodrigo et al., 1997).

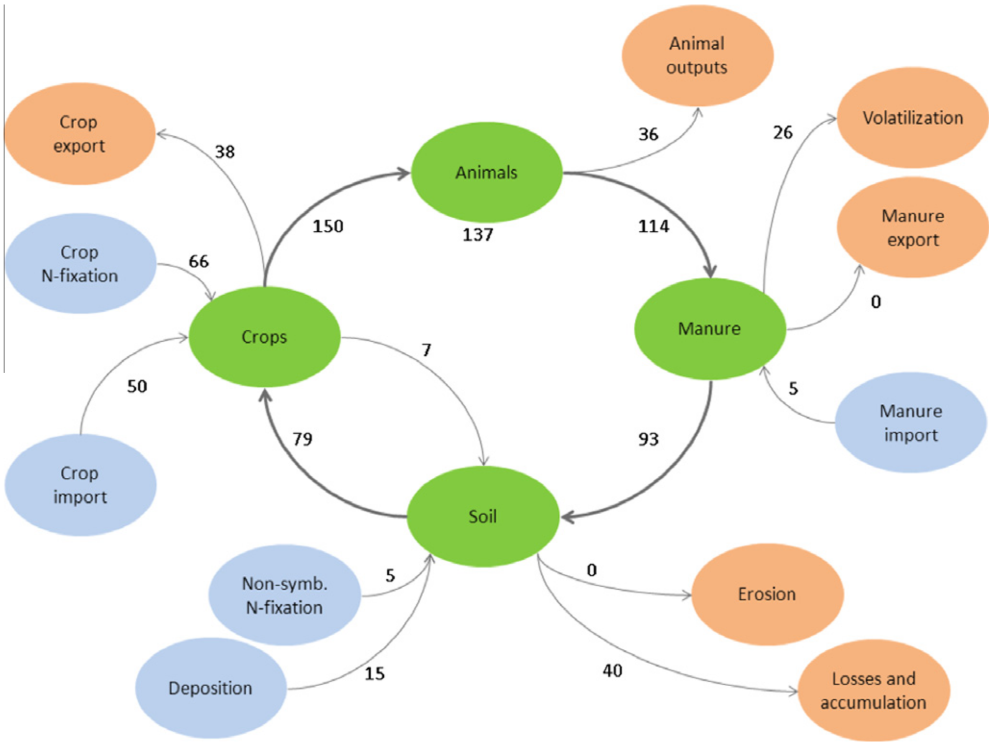

Fig. 2. Visualization of the nitrogen cycle in FarmDESIGN, illustrated with data from the Ter Linde mixed farm.

- Average temperature (T; °C) during the moist period, following a Van't Hoff function wherein Q_{10} is a constant representing the increase in organic matter degradation for an increase in temperature of 10 °C (Rodrigo et al., 1997), and relative to a reference temperature (T_{REF}; 9.5 °C under conditions in The Netherlands; $Q_{10} = 2$, Kätterer et al., 1998).
- A dimensionless soil texture correction factor that is used to estimate the effect of increased physical protection of organic matter in soils with higher clay content (Ladd et al., 1977; Hassink, 1994) (U; 1.2 for sandy soils, 1.0 for loam and 0.8 for clay). Effects of differences in tillage frequency and intensity can be specified by adjusting the structure factor U, thus affecting the degradation rates of all organic matter fractions.

$$f = \frac{1}{U \cdot \frac{W}{365} \cdot Q_{10}^{(T - T_{\mathrm{REF}})/10}} \qquad (1)$$

The function $f(-)$ is used to correct on-farm organic matter degradation rates when the number of days with pF > 3.5 is smaller than 365, average temperature deviates from 9.5 °C, and soil type is not loam (see below). The amount of newly added organic matter from various sources (crop residues, green manures, feed losses, etc.) that contributes to organic matter accumulation is determined by the humification coefficient (h; kg kg^{-1}), which defines the proportion of the organic matter remaining 1 year after application (Janssen, 1984, 1996) at the reference temperature. The humification coefficient can be specified for each organic matter source.

The total organic matter input from green manures ($\mathrm{OM_{GreenManure}}$; kg) is calculated from the dry matter of each crop product $p = \{1, \ldots, n_p\}$ that is used as green manure ($\mathrm{DM}_{\mathrm{GreenManure},p}$; kg) and the organic matter content, derived from the fraction of ash in dry matter ($F_{A,p}$; kg kg^{-1}).

$$\mathrm{OM_{GreenManure}} = \sum_{p=1}^{n_p} DM_{\mathrm{GreenManure},p} \cdot (1 - F_{A,p}) \cdot h_p \cdot f \qquad (2)$$

The organic matter input from crop residues ($\mathrm{OM_{CropResidue}}$) depends on the organic matter input by roots and stubble per crop c ($\mathrm{OM}_{\mathrm{RootStubble},c}$), the crop's humification coefficient (h_c; kg kg^{-1}) and crop area (A_c), and is summed for all crops $c = \{1, \ldots, n_c\}$:

$$\mathrm{OM_{CropResidue}} = \sum_{c=1}^{n_c} A_c \cdot \mathrm{DM}_{\mathrm{RootStubble},c}(1 - F_{A,c}) \cdot h_c \cdot f \qquad (3)$$

The organic matter input from feed losses ($\mathrm{OM_{FeedLoss}}$) is calculated from the dry matter of crop products with destination as animal feed ($\mathrm{DM}_{\mathrm{AnimalFeed},p}$; kg), the fraction of feed loss ($F_{L,p}$; kg kg^{-1}) of the crop product, the ash content ($F_{A,p}$; kg kg^{-1}) and the humification coefficient (h_p; kg kg^{-1}).

$$\mathrm{OM_{FeedLoss}} = \sum_{p=1}^{n_p} \mathrm{DM}_{\mathrm{AnimalFeed},p} \cdot F_{L,p} \cdot (1 - F_{A,p}) \cdot h_p \cdot f \qquad (4)$$

The amount of organic matter from manure produced on the farm ($\mathrm{OM_{Manure}}$) is partly degraded in the year in which it is produced ($\mathrm{OM_{ManureDegraded}}$), both amounts are calculated as described in Section 2.2.5. Organic matter in imported manure ($\mathrm{OM_{ImportedManure}}$) is derived from the amount of manure imported and the organic matter content of the manure.

Losses of OM occur due to soil OM degradation ($\mathrm{OM_{SoilDegraded}}$) and erosion ($\mathrm{OM_{Erosion}}$). The amount of organic matter in the farmed soil is calculated on the basis of the farm area A (ha), the bulk density of the soil (B; kg dm^{-3}) for a given depth (D; m) and the soil organic matter content ($F_{\mathrm{OM},s}$; kg kg^{-1}). Parameter k_S (kg kg^{-1}) is the fraction of soil organic matter degraded on an annual basis.

$$\mathrm{OM_{SoilDegraded}} = A \cdot F_{\mathrm{OM},s} \cdot B \cdot D \cdot k_S \cdot f \qquad (5)$$

The amount of OM eroded ($\mathrm{OM_{Erosion}}$) is determined by soil loss (SL; mm), the density of the eroded material (E; kg dry matter ha^{-1} mm^{-1}) and the ash content of the soil ($F_{A,s}$; kg kg^{-1}).

$$\mathrm{OM_{Erosion}} = A \cdot \mathrm{SL_{Erosion}} \cdot E \cdot (1 - F_{A,s}) \qquad (6)$$

Finally, the total OM balance is calculated as:

$$\begin{aligned}\mathrm{OM}_{\mathrm{Balance}} = {} & \mathrm{OM}_{\mathrm{CropResidue}} + \mathrm{OM}_{\mathrm{GreenManure}} + \mathrm{OM}_{\mathrm{FeedLoss}} \\ & + \mathrm{OM}_{\mathrm{Manure}} + \mathrm{OM}_{\mathrm{ImportedManure}} - \mathrm{OM}_{\mathrm{SoilDegraded}} \\ & - \mathrm{OM}_{\mathrm{ManureDegraded}} - \mathrm{OM}_{\mathrm{Erosion}} \end{aligned} \tag{7}$$

2.2.5. Manure production, breakdown and losses

The amount of feces dry matter produced ($\mathrm{DM}_{\mathrm{Manure}}$; kg) depends on the amount of dry matter in bedding material in the stable ($\mathrm{DM}_{\mathrm{Bedding}}$; kg) and the amounts of dry matter in the various crop and animal products that are supplied as feed ($\mathrm{DM}_{\mathrm{AnimalFeed},p}$ for each product p; kg) corrected for the feed losses ($F_{L,p}$; kg kg^{-1}) and for apparent dry matter digestibility (DMD_p; kg kg^{-1}) of each product:

$$\mathrm{DM}_{\mathrm{Manure}} = \sum_{p=1}^{n_p} \mathrm{DM}_{\mathrm{AnimalFeed},p} \cdot (1 - F_{L,p}) \cdot \mathrm{DMD}_p + \mathrm{DM}_{\mathrm{Bedding}} \tag{8}$$

The amounts of OM ($\mathrm{OM}_{\mathrm{Manure}}$) and C in manure are calculated using the ash content of the crop and animal products and assuming a C content in organic matter of 50%. The total amounts of N, P and K in manure (NM, PM and KM; in both urine and feces) are derived from the difference between intake and products of the animals, as demonstrated only for N in Eq. (9).

$$\mathrm{NM}_{\mathrm{Manure}} = \sum_{p=1}^{n_p} (\mathrm{DM}_{\mathrm{AnimalFeed},p} \cdot F_{N,p} \cdot (1 - F_{L,p})) - \mathrm{NM}_{\mathrm{AnimalProducts}} \tag{9}$$

where $F_{\mathrm{N},p}$ is the N content of feed component p, $\mathrm{NM}_{\mathrm{AnimalProducts}}$ (kg) is the summed amount of N in animal products such as milk, meat, eggs and wool. It is assumed that for animal products that are fed to animals (for instance milk for calves) no losses occur during feeding. The total amount of feces N produced is estimated as fraction of the N intake at herd level ($\mathrm{NM}_{\mathrm{Intake}}$; kg):

$$\mathrm{NM}_{\mathrm{Feces}} = (1 - F_{\mathrm{DN}}) \cdot \mathrm{NM}_{\mathrm{Intake}} \tag{10a}$$

where F_{DN} (kg kg^{-1}) is the apparent digestibility of nitrogen, which is estimated using an empirical relation proposed by Holter and Reid (1959, p. 1345) based on the N content of the ration (F_{N}; kg kg^{-1}):

$$F_{\mathrm{DN}} = \frac{92.9 - 0.5568/F_{\mathrm{N}}}{100} \tag{10b}$$

The amount of urine N produced is calculated as the difference between nitrogen intake and outputs in products and feces:

$$\mathrm{NM}_{\mathrm{Urine}} = \mathrm{NM}_{\mathrm{Intake}} - \mathrm{NM}_{\mathrm{AnimalProducts}} - \mathrm{NM}_{\mathrm{Feces}} \tag{10c}$$

In these calculations the animal intake of DM and N of the whole herd ($\mathrm{DM}_{\mathrm{Intake}}$ and $\mathrm{NM}_{\mathrm{Intake}}$; kg) is used, and no distinction is made per animal type, production level or age group. Since hardly any P is found in ruminant urine (McDowell, 1992), P-content of feces is calculated by subtracting the quantity of P in milk and meat from the total quantity in the fodder. Almost all K in feed is excreted, and the largest part of about 90% is found in the urine (McDowell, 1992).

$$\mathrm{PM}_{\mathrm{Feces}} = \mathrm{PM}_{\mathrm{Intake}} - \mathrm{PM}_{\mathrm{AnimalProducts}} \tag{11a}$$

$$\mathrm{PM}_{\mathrm{Urine}} = 0 \tag{11b}$$

$$\mathrm{KM}_{\mathrm{Feces}} = 0.1 \cdot \mathrm{KM}_{\mathrm{Intake}} \tag{12a}$$

$$\mathrm{KM}_{\mathrm{Urine}} = 0.9 \cdot \mathrm{KM}_{\mathrm{Intake}} \tag{12b}$$

Manure produced on the farm can be deposited at three sites: in the pasture, in the stable and in the yard. A yard or feedlot is an outdoors confined area, often close to the stable, were animals are kept during a limited time of the day, for instance before and/or after milking. The excretion of manure at the different sites is assumed to be proportional to the time spent at each site. Per site one or more types of manure can be produced, depending on storage and treatment of the manure. An example is the production of both slurry and farm-yard-manure in a stable. The proportions will differ depending on housing type etc., and can be specified in the manure parameters.

From the time spent at each site and the proportion of different types of manure produced ($m = \{1, \ldots, n_m\}$, for instance pasture manure, slurry or farm yard manure, dependent on the grazing and housing systems) at each site (fraction excreted: $F_{E,m}$; kg kg^{-1}), the amounts of each manure type is calculated in terms of DM, OM, N, P and K. Bedding material is added only to farm yard manure (FYM). Ruminant urine contains nitrogen in forms that can be rapidly mineralized, whereas nitrogen in feces is predominantly in organic form (Whitehead, 1995; Kirchmann and Lundvall, 1998). Amounts of mineral and organic N are quantified for each manure type m as:

$$\mathrm{NM}_{\mathrm{Mineral},m} = F_{E,m} * (0.03 * \mathrm{NM}_{\mathrm{Feces}} + \mathrm{NM}_{\mathrm{Urine}}) \tag{13}$$

$$\mathrm{NM}_{\mathrm{Organic},m} = F_{E,m} * 0.97 * \mathrm{NM}_{\mathrm{Feces}} + \mathrm{NM}_{\mathrm{Bedding}} \tag{14}$$

where $\mathrm{NM}_{\mathrm{Bedding}}$ is only applied for FYM. During storage of manure, part of the organic matter is degraded and nitrogen can be immobilized or mineralized and partly lost. The degradation and mineralization processes take place in aerobic and/or anaerobic conditions, and a proportional division between these conditions is specified per manure type. The OM degradation ($\mathrm{OM}_{\mathrm{ManureDegraded}}$; kg) and N mineralization ($\mathrm{NM}_{\mathrm{ManureReleased}}$; kg) are calculated for each manure type and with separate sets of parameters for aerobic and anaerobic conditions using Eqs. (15) and (16):

$$\mathrm{OM}_{\mathrm{ManureDegraded}} = k_M * OM_{\mathrm{Manure}} \tag{15}$$

$$\mathrm{NM}_{\mathrm{ManureReleased}} = \frac{0.5 * \mathrm{OM}_{\mathrm{ManureDegraded}}}{1 - \varepsilon} \cdot \left(\frac{\mathrm{NM}_{\mathrm{Manure}}}{\mathrm{CM}_{\mathrm{Manure}}} - \frac{\varepsilon}{r} \right) \tag{16}$$

where k_M (kg kg^{-1}) is the fraction of manure degraded, ε is the efficiency of conversion of organic matter to microbial biomass (kg kg^{-1}), $\mathrm{CM}_{\mathrm{Manure}}$ is the carbon mass in manure and r is the C:N ratio of microbial biomass (kg kg^{-1}) (Janssen, 1996). The factor 0.5 represents the carbon content of organic matter in manure. Eq. (16) represents the balance between nitrogen release due to degradation of OM and N incorporation into organic matter due to the growth of microbial biomass (Groot et al., 2003; Reijs et al., 2007). The organic matter loss is corrected for the microbial biomass synthesis (from apparent to true degradation) by dividing by $(1 - \varepsilon)$. Losses of mineral nitrogen from manure are calculated directly after excretion, during storage and after application on the field using loss fractions that are specific for each manure type. After application to the field the manure organic matter will be further degraded. The fraction of OM remaining at the end of the year of application is given by the humification coefficient h (kg kg^{-1}) of the manure type, which is affected by environmental conditions as described by f (Eq. (1)). Total degradation of organic matter during storage and after application is calculated for each manure type as:

$$\mathrm{OM}_{\mathrm{ManureDegraded}} = (1 - h \cdot f) \cdot \mathrm{OM}_{\mathrm{Manure}} \tag{17}$$

2.2.6. Labor balance

A distinction is made between regular and casual labor. Regular labor is provided by the members of the farm family and by hired skilled employees ($\mathrm{LR}_{\mathrm{Input}}$; h). Casual labor concerns temporarily hired personnel, used in particular during labor peaks, for instance for weeding and harvesting. It is performed by less skilled workers and has a lower price than regular labor. In addition, contract work can be performed for crop cultivation, which is included in the calculations of the crop's gross margin. Contract work is not included in the labor balance.

A fixed amount of regular labor is needed for general management of the farm ($\mathrm{LR_{Farm}}$; h). This labor requirement will be only partly dependent on the farm set-up, and cannot be attributed directly to work on crops or animals. Labor requirement related to crop cultivation is determined by the regular and casual labor requirement per ha of the crop (LR_c and LC_c; h ha^{-1}) and crop area (A_c; ha). Labor requirement related to animal husbandry comprises only regular (skilled) labor. A fixed amount of labor is required for herd and stable management ($\mathrm{LR_{Herd}}$; h) and a part of the labor is dependent on the animal type $a = \{1,\ldots,n_a\}$(LR_a; h animal^{-1}) and the number of animals N_a. The labor balances ($\mathrm{LR_{Balance}}$ and $\mathrm{LC_{Balance}}$; h) are calculated as:

$$\mathrm{LR_{Balance}} = \mathrm{LR_{Farm}} + \mathrm{LR_{Herd}} + \sum_{c=1}^{n_c} A_c * \mathrm{LR}_c + \sum_{a=1}^{n_a} N_a * \mathrm{LR}_a - \mathrm{LR_{Input}} \tag{18}$$

$$\mathrm{LC_{Balance}} = \sum_{c=1}^{n_c} A_c * \mathrm{LC}_c \tag{19}$$

Positive values of LR and LC indicate that additional labor should be hired, whereas negative values (that can occur only for regular labor) indicate that there is a surplus of labor on the farm and the members of the farm family could try to find employment outside the farm.

2.2.7. Economic calculations

The returns of the farm originate from the crop and animal gross margins that include revenues and variables costs, and additional costs, both variable (for manure and labor) and fixed (for land, buildings, machinery and general).

The amount of animal products (AP) is determined by the number of animals of a particular type (N_a) and their production of milk (M_a; kg day^{-1}) and meat (resulting from growth G_a (kg day^{-1}) and the fraction carcass (R_a; kg kg^{-1})). Produced milk and meat are thus calculated as follows:

$$\mathrm{AP_{Milk}} = \sum_{a=1}^{n_a} 365 \cdot N_a \cdot M_a \tag{20}$$

$$AP_{Meat} = \sum_{a=1}^{n_a} 365 \cdot N_a \cdot G_a \cdot R_a \tag{21}$$

The gross margin of the crops (MC; expressed in the selected currency) depends on the revenue from crop products as affected by their fresh yield ($\mathrm{FM}_{c,p}$; kg ha^{-1}) and price ($\mathrm{P}_{c,p}$; currency kg^{-1}), the cultivated area, the costs for cultivation, and crop-specific subsidies (costs C_c, contract work W_c and subsidy S_c; all expressed in currency ha^{-1}).

$$\mathrm{MC} = \sum_{c=1}^{n_c} A_c \cdot \left(\sum_{p=1}^{n_p} (\mathrm{FM}_{c,p} \cdot P_{c,p}) - C_c - W_c - S_c \right) \tag{22}$$

The costs for animal production are related to feeding, bedding, interest and other costs. Both crop products and animal products $q = \{1,\ldots,n_q\}$ (in practice only for milk) can be fed to animals, and feed costs (CF) are calculated as:

$$\mathrm{CF} = \sum_{p=1}^{n_p} (\mathrm{DM}_{AnimalFeed,p}/F_{\mathrm{DM},p}) \cdot P_p + \sum_{q=1}^{n_q} \mathrm{AP}_{\mathrm{AnimalFeed},q} \cdot P_q \tag{23}$$

where $F_{\mathrm{DM},p}$ is the dry matter fraction in the fresh mass of a crop product p. Similarly, the costs of bedding are calculated as:

$$\mathrm{CB} = \sum_{p=1}^{n_p} (\mathrm{DM}_{\mathrm{Bedding},p}/F_{DM,p}) * P_p \tag{24}$$

The animal herd kept on the farm represents capital for which interest should be calculated on the basis of the total carcass weight (from body weight BW_a (kg) and carcass fraction R_a (kg kg^{-1})) of the herd, the meat price (P_{Meat}) and the interest rate (I; %):

$$\mathrm{CI} = \sum_{a=1}^{n_a} n_a \cdot \mathrm{BW}_a \cdot R_a \cdot P_{\mathrm{Meat}} \cdot I/100 \tag{25}$$

From the results of the equations presented above the gross margin for animal husbandry (MA; currency) can be derived as:

$$\mathrm{MA} = \sum_{q=1}^{n_q} (\mathrm{AP}_q \cdot P_q) - \mathrm{CF} - \mathrm{CB} - \mathrm{CI} - \mathrm{CO} \tag{26}$$

where CO are other animal costs, expressed in the selected currency.

The additional costs can be variable costs related to inputs such as manure (CM) and regular and casual labor (CR and CC), and fixed costs for land (CL), assets such as buildings and machinery (CA) and some general costs (CG). The costs for manures (CM; $m = \{1,\ldots,n_m\}$) depend on the amount (fresh mass FM; kg) and price (P_m; currency kg^{-1}) of externally purchased manures.

$$\mathrm{CM} = \sum_{m=1}^{n_m} \mathrm{FM}_m \cdot P_m \tag{27}$$

The costs for assets (CA) such as buildings and machines ($s = \{1,\ldots,n_s\}$) result from depreciation, operation costs and interest over the investment. Depreciation (V_s; %) and operational costs (C_s; %) of buildings and machines are expressed as a percentage of the capital invested. A correction factor g_s for the interest rate is used to account for the fraction of the investment that has already been discounted to calculate interest costs for buildings ($g = 0.5$) and machines ($g = 0.6$), respectively:

$$\mathrm{CA} = \sum_{s=1}^{n_s} n_s * P_s * (V_s + C_s + g_s \cdot I)/100 \tag{28}$$

The costs for regular and casual labor (CR and CC) depend on the price of regular and of casual labor (P_{LR} and P_{LC}; currency h^{-1}) and are calculated separately. The amount of labor used can be derived from the equations in Section 2.2.6.

$$\mathrm{CR} = P_{\mathrm{LR}} \cdot \left(\mathrm{LR_{Farm}} + \mathrm{LR_{Herd}} + \sum_{c=1}^{n_c} A_c \cdot \mathrm{LR}_c + \sum_{a=1}^{n_a} n_a \cdot \mathrm{LR}_a \right) \tag{29}$$

$$\mathrm{CC} = P_{\mathrm{LC}} \cdot \sum_{c=1}^{n_c} A_c \cdot \mathrm{LC}_c \tag{30}$$

The general costs (CG; currency) are represented by a fixed input parameter; costs of land (CL; currency) are calculated by multiplying the farm area with land costs per area. The operating profit (OP) is calculated as:

$$\mathrm{OP} = \mathrm{MC} + \mathrm{MA} - \mathrm{CM} - \mathrm{CA} - \mathrm{CR} - \mathrm{CC} - \mathrm{CL} - \mathrm{CG} \tag{31}$$

2.3. Pareto-based Differential Evolution

2.3.1. Multi-objective optimization

The trade-offs between socio-economic and environmental objectives were explored by linking the farm balance model to a multi-objective Pareto-based Differential Evolution algorithm. The exploration of the trade-offs between objectives can be formulated as a multi-objective design problem, which can be generally stated as follows.

$$\text{Max } \mathbf{U}(\mathbf{x}) = (U_1(\mathbf{x}), U_2(\mathbf{x}), \ldots, U_k(\mathbf{x}))^T \tag{32}$$

$$\mathbf{x} = (x_1, x_2, \ldots, x_n)^T \tag{33}$$

Subject to i constraints:

$$g_i(\mathbf{x}) \leqslant h_i \tag{34}$$

where $U_1(\mathbf{x}), \ldots, U_k(\mathbf{x})$ are the objective functions that are simultaneously maximized or minimized, and $(x_1, \ldots, x_n)$ are the decision variables that represent the farm-specific adjustable parameters, to define alternative farm configurations. The decision variables can take on a predescribed array of values, $\mathbf{x} \in S$, where S is the solution or parameter space. Constraints in Eq. (34) can arise from the problem formulation, for instance by limitations on farm model results related to a specific configuration of decision variables.

2.3.2. Differential Evolution

Differential Evolution (DE; Storn and Price, 1997) belongs to the family of Evolutionary Algorithms, consisting of adaptive search techniques based on the principles of natural evolution. Genetic operators for reproduction, selection, mutation and crossover (the latter only in so-called Genetic Algorithms) are applied to a set of solutions or genotypes, consisting of alleles. In our application the genotypes represent alternative farming system configurations and the alleles are decision variables in which tactical choices concerning the allocation of farm inputs (crop areas, product destinations, animal numbers, etc.) are encoded as a real number. A genotype is a multi-dimensional vector $p = (p_1, \ldots, p_z)^T$ of z alleles. Each allele p_i is initialized as $p_{i,0}$ by assigning a random number within the range allowed for individual decision variables.

A new generation $t + 1$ is created by applying mutation and selection operators on each of the individuals in the population P of the current generation t. The first step of the reproduction process is generation of a trial population P' that contains a counterpart for each individual in the parent population P, produced by parameterized uniform crossover of a parent 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 t. The allele values of the individual in the trial population are taken from the mutation vector with probability C_R and with probability $(1 - C_R)$ copied from the parent:

$$P'_{i,t+1} = \begin{cases} c_{3,i} + F \times (c_{1,i} - c_{2,i}) & \text{if } r_i < C_R \\ p_{i,t} & \text{otherwise} \end{cases} \tag{35}$$

where r_i is a uniformly distributed random variable. The parameter $F \in [0,2]$ is a parameter that controls the amplification of differential variations. After a mutation, the value of $p'_{i,t+1}$ can extend outside of the allowed range of the search space. For allele values that violate the boundary constraints the 'back folding' repair rule is applied (Groot et al., 2010).

A trial genotype $p'_{i,t+1}$ replaces p_t if it outperforms the parent genotype. Here, better performance is interpreted as a better Pareto ranking or a location in a less crowded area of the search space than the parent genotype. These performance criteria are explained below. Population size N is determined by the number of alleles in the genotype z and a multiplication factor M. The last parameter in the DE algorithm is the number of generations G, which serves as the stopping criterion. The default parameter values as employed in this study for F (=0.15), C_R (=0.85), M (=40) and G (=10,000) were derived from factorial analysis in preliminary optimization runs, where G was chosen such that the volume of the solution space no longer expanded.

2.3.3. Pareto-based selection

The first criterion for the performance of a solution is its Pareto rank as proposed by Goldberg (1989). Individuals in the population are Pareto-optimal 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. In such case, there is no objective basis to discard the individual. These individuals are called non-dominated and receive rank 1. This set of solutions is called the trade-off frontier. The next step in Pareto-ranking the entire population of solutions is to remove the individuals of rank 1 from the population and identify a new set of non-dominated individuals, which is assigned rank 2. This process is continued until all individuals in the population are assigned a Pareto rank. When the prior information of the performance of the original farming system is used, the ranking mechanism of Goldberg (1989) may be slightly adjusted to improve the exploration of that part of the solution space where solutions are found that perform better than the original farm configuration. In this case, a (superior) rank 0 (zero) can be assigned to solutions that perform better than the original configuration for all the objectives (Fig. 3).

If two solutions have the same rank, a second selection criterion, the crowding distance, is taken into account. The metric Θ represents the within-rank solution density and is calculated from the normalized distance from solution i to the nearest solution in the search space, as follows (Deb et al., 2002):

$$\Theta_i = \sum_{j=1}^{k} \frac{|d_{i,j} - \overline{d_j}|}{|B_j|} \tag{36}$$

where B_j is the range of objective j, which is calculated as the difference between the minimum and maximum values of objective j. Variable $d_{i,j}$ denotes the Euclidian distance between solution i and the nearest neighboring solution within the Pareto front of a given rank and the parameter $\bar{d}_j$ is the average of these distances. An individual is replaced by a trial solution of the same rank if the latter is located in a less densely populated part of the solution space.

2.3.4. Optimization runs

The original farm configuration was used as a starting point for the optimization. The genotypes representing this staring point constituted 20% of the initial population and the other genotypes in the population (80%) were randomly generated. Reasons to retain the original farm configuration are that we are searching for improvements of the farm configuration relative to the current situation, and that the constraints regarding feed balance and crop areas (see Section 3.2) are too restrictive to allow generation of a valid farm configuration from a completely random process.

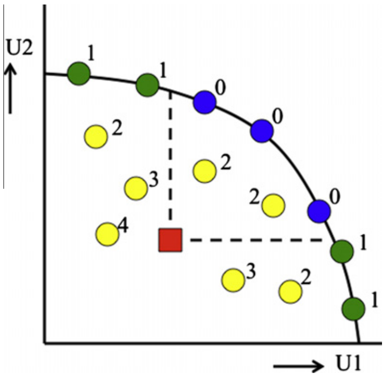

Fig. 3. Pareto-based ranking scheme illustrated for a solution space of two objectives U1 and U2 that are maximized. Ranks 1–4 are assigned using the ranking mechanism proposed by Goldberg (1989). Green and blue circles represent Pareto-optimal (non-dominated, rank 1) solutions and yellow symbols are dominated solutions of ranks 2–4. The procedure was extended by assigning rank 0 (blue circles) to Pareto-optimal solutions that outperform the original farm configuration (red square) for all objectives. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We report on two optimization runs, one where we employed the authentic Goldberg (1989) Pareto ranking procedure for full trade-off frontier exploration, and another in which the adjusted ranking mechanism (Fig. 3) was used to search for solutions that represented global improvement for all the objectives when compared to the original farming system. Both ranking mechanisms were combined with the crowding metric Θ.

2.4. Implementation

The model and the optimization algorithm were developed within the Microsoft Visual Studio® using the C++ and C# languages, using object-oriented software development approaches. The database was implemented in Microsoft Access®.

3. Case study farm

3.1. Original farm configuration

The model was applied to a 96 ha mixed organic farm named 'Ter Linde', located in Oostkapelle, The Netherlands. On the farm, the cultivated area was divided into two rotations that were laid down in almost concentric circles around a core consisting of the farm buildings and an adjacent area consisting of other crops (whole crop silage and extensively used meadows) (Table 1), and a small area for small vegetable crops (for home consumption; not included in the analysis). Both the exterior rotation (45.5 ha) and the interior rotation (35.0 ha) included cash crops of which the products were exported from the farm, and feed crops and grasslands that were used for grazing or mowing (Table 1). Straw for bedding of animals in the stable and a small amount of feed were imported into the farm. Potatoes, black beans and pumpkin were grown either as single crops or followed by a green manure. The animal herd consisted of 76 milk cows and their replacement: 11 calves and 11 yearlings resulting in a replacement rate of 15% per year. During the 200 days grazing season the animals were outdoors for day grazing only.

3.2. Decision variables, objectives and constraints

Four objectives were identified in interaction with the farmers. These objectives were to maximize operating profit so as to generate sufficient income, to minimize the labor balance by optimizing allocation of labor resources, to maximize the organic matter balance to improve soil structure, and to minimize nitrogen soil losses (i.e. leaching and denitrification).

The decision variables concerned tactical choices of the areas of cultivated crops (including feed crops), the destination of crop products and management variables for the animal herd (Table 1). To calculate crop areas a minimum rotation length of 6 years was assumed, resulting in maximum crop areas of 7.5 ha and 6 ha for the exterior and interior rotations, respectively. For feed crops two decision variables per crop product are needed, specifying the total amount fed and the fraction that is fed during the stable period. The available amounts of the products used as feed or green manure from crops cultivated on-farm are calculated from the cropped area and the yield per ha, so no separate decision variables for the amount of these feeds and green manures are required (Table 1). During the optimization, the number of calves and yearlings is derived from the number of milk cows and the replacement rate.

Constraints were set for the total farm area (sum of all cropped areas) and the crop areas within each rotation (Table 2); these cultivated areas should not exceed the available areas. A crop group was defined for root crops, here comprising potatoes and the various beets, as these are associated with a high risk of damage to soil structure during harvesting. The frequency of cultivation of these root crops was constrained to 1 in 4 years. Three crop groups were formed for potatoes, black beans and pumpkin that can be cultivated with and without green manures. A constraint for the frequency of cultivation of these groups (maximum 1 in 6 years) restricts the total area of each crop in the exterior rotation to 7.5 ha, whereas in the optimization each crop can be selected both with and without green manures can be selected. The ration should be balanced in the grazing and stable periods and maximum (positive or negative) deviations of supply relative to animal requirement were used as constraints. Dry matter supply should not exceed the animal feed intake capacity, whereas energy and protein supply should not be much lower than required and no excessive surpluses should occur to avoid animal health problems and undesired losses due to inefficiencies. To avoid nutrient mining minimum values for acceptable nutrient losses (for N) and balances (for P and K) were applied as constraints. Nitrogen losses can be considered as unavoidable, also when management is highly accurate, and therefore calculated losses lower than ca. 20 kg N ha^{-1} year^{-1} indicate that the N availability in the soil is so low that target yields would not be attainable. Production rights (milk quotum) limit the total amount of milk that can be produced on the farm. A constraint was added to balance the use of bedding material for animals in the stable with the supply of bedding material, in this case only straw.

4. Results

The complexity of the farming system with multiple rotations and a combination of arable cropping and dairy production could be represented well by the model. The original farming system resulted in an operating profit of 29.5 k€ (Table 3), in which the labor costs of the farmer's family was already accounted for. The gross margin of the cropping activities (281 k€) was higher than that of the animal husbandry (132 k€). Total labor requirement for general farm management, crop cultivation and herd management was 5696 h, whereas the labor input by the farmer's family amounted to 4000 h. Thus, the labor balance had a positive value of 1698 h (Table 3), indicating that additional labor should be hired to perform all planned tasks. For the environmental objectives, an OM balance of -189 kg ha^{-1} was calculated (Table 3), indicating that the breakdown of manure and soil OM was slightly higher (2782 kg ha^{-1}) than the inputs of OM from crop residues, green manures and animal manure (2563 kg ha^{-1}). The soil N losses through nitrate leaching and denitrification amounted to 40 kg N ha^{-1}, the estimated ammonia volatilization from animal manures produce on-farm was 26 N kg ha^{-1} (Fig. 2).

The exploration of trade-offs among the four objectives using optimization demonstrated that reconfiguration of the components on the farm could lead to substantial improvements in operating profit and organic matter balance, and in lower labor balance and soil N losses (Fig. 4). At the same level of performance of one of the objectives, various alternatives with contrasting performance in other objectives were generated. Trade-offs became apparent between operating profit and labor balance, and between OM balance and N losses. A larger operating profit was associated with higher labor balance (Fig. 4a) and smaller OM balance (Fig. 4b) and a larger OM balance resulted in larger soil N losses (Fig. 4f). Synergies were found between labor balance and soil N, since solutions with lower labor balance often had lower soil N losses (Fig. 4e).

Although the best results for individual objectives could only be reached at the expense of other objectives (green symbols in Fig. 4), ca. 15% of the solutions represented alternative farming

Table 1
Overview of cultivated crops, crop products and their destination, and animal production on the Ter Linde farm based on data collected in 2010 (column Original). Columns labeled Minimum and Maximum indicate the allowed range of variation in the optimization procedure in case a variable is used as a decision variable. The used amounts of on-farm produced feeds and green manures (indicated with *) are directly linked to the cropped area (using crop yield), so no separate decision variable is included. Products associated with the crop 'External' are imported.

Areas of crops in rotations (ha)				
Rotation	Crop	Original	Minimum	Maximum
Interior rotation	Whole crop silage 1 (WCS)	5.0	0.0	6.0
	Celeriac	4.5	0.0	6.0
	Turnip	0.5	–	–
	Parsnip	1.0	–	–
	Sugar beet	3.0	0.0	6.0
	Fodder beet	1.0	0.0	6.0
	Maize silage	0.0	0.0	6.0
	Grass clover 1 (grazing)	20.0	0.0	20.0
Exterior rotation	Chicory	3.0	0.0	7.5
	Celeriac	6.5	0.0	7.5
	Red beet	2.0	0.0	7.5
	Sugar beet	1.5	0.0	7.5
	Potatoes	4.0	0.0	7.5
	Potatoes and green manure (GM)	2.5	0.0	7.5
	Black beans	4.0	0.0	7.5
	Black beans and GM	2.5	0.0	7.5
	Pumpkin	4.0	0.0	7.5
	Pumpkin and GM	2.5	0.0	7.5
	Grass clover 2 (mowing)	13.0	0.0	15.0
Other crops	Whole crop silage 2	1.2	-	-
	Grass clover 3 (grazing)	2.5	0.0	5.0
	Grass clover 4 (extensive use)	3.3	0.0	5.0
Amount of crop products used as feed (kg dry matter (fraction used in stable period))				
Crop	Product	Original	Minimum	Maximum
External	Beet pulp	70,000 (0.2)	0 (0.2)	100,000 (0.6)
	Grass clover silage ext.	40,000 (1.0)	0 (0.5)	100,000 (1.0)
	Concentrate	66,000 (1.0)	0 (0.5)	100,000 (1.0)
Maize	Maize silage*	0 (0.0)	(0.0)	(1.0)
Fodder beet	Fodder beet*	11,000 (1.0)	(0.9)	(1.0)
WCS	WCS Silage*	46,500 (0.0)	(0.0)	(0.5)
Grass clover 1	Grazed pasture 1*	120,000 (0.0)	(-)	(-)
Grass clover 2	Grass clover silage 2*	143,000 (1.0)	(0.0)	(1.0)
Grass clover 3	Grass clover silage 3*	18,750 (0.0)	(–)	(–)
Grass clover 4	Hay*	11,550 (1.0)	(0.5)	(1.0)
	Grazed pasture 2*	6600 (0.0)	(–)	(–)
Amount of crop products use as green manure (kg dry matter)				
Potatoes and GM	Green manure*	6250	0	18,750
Black beans and GM	Green manure*	6250	0	18,750
Pumpkin and GM	Green manure*	6250	0	18,750
Amount of crop products used for bedding (kg dry matter)				
External	Straw	125,000	0	250,000
Animals kept on the farm				
Animal type	Variable	Original	Minimum	Maximum
Milk cows	Number	76	30	90
	Milk production (kg day^{-1})	22.0	15.0	28.0
	Replacement rate (per year)	0.15	0.10	0.45
	Bedding supplied (kg day^{-1})	4.0	2.0	10.0

systems that performed better than the original system in all four objectives (blue symbols in Fig. 4). When the performance of the original farming system was explicitly used in the optimization to assign a 'superior' rank 0 to solutions that performed better for all objectives (cf. Fig. 3), the resulting set of solutions contained only solutions that performed better for the four objectives (Fig. 5). The efficiency gain in the optimization was achieved by extending the original algorithm to favor solutions better than the current configuration. Based on this solution set, Table 3 presents the farming systems configurations that performed best for each of the objectives. The contribution of each decision variable to the objective value was approximated by changing the value of the decision variable in the original model to the value found in the optimal solution and expressing the resulting change in the objective value relative to the original value (Δ, expressed in% change in the desired direction; Table 3). When aiming for maximum operating profit a considerable improvement from 29 k€ to 75 k€ would be possible by increasing the milk production per cow and by increasing the cultivated area of chicory and pumpkin without green manures. These changes, however, do not lead to much improvement of the other objectives. Maximizing soil organic matter balance would be most supported by considerably increasing the amount of straw as bedding material, which ends up in the manure. Decreasing the area of pumpkins also contributes to SOM increases as crops that contribute more to SOM than pumpkins occupy the area. Reducing the herd size would decrease both soil nitrogen losses and labor requirement, as well as reducing area of grass-clover for mowing that is used for animal feed (Table 3). The latter will result in lower nitrogen inputs into the system through symbiotic nitrogen fixation by the white clover. The labor balance

Table 2
Constraints applied during the multi-objective optimization of the farming system at the Ter Linde farm. The values for the original farm configuration are given, and the minimum and maximum of the allowed ranges of the variables are specified.

Variable	Original	Minimum	Maximum
Farm area (ha)	95.5	90.0	96.0
Area exterior rotation (ha)	45.5	0	45.5
Area interior rotation (ha)	35.0	0	35.0
Area other crops (ha)	15.0	0	15.0
Frequency of root crops in the exterior rotation	0.08	0	0.25
Frequency of root crops in the interior rotation	0.11	0	0.25
Frequency of potatoes in the exterior rotation	0.14	0	0.167
Frequency of black beans in the exterior rotation	0.14	0	0.167
Frequency of pumpkin in the exterior rotation	0.14	0	0.167
Deviation in feed balance intake grazing period (%)	−0.7	–	0
Deviation in feed balance energy grazing period (%)	1.3	−10	10
Deviation in feed balance protein grazing period (%)	4.0	−5	20
Deviation in feed balance intake stable period (%)	−5.7	–	0
Deviation in feed balance energy stable period (%)	−0.3	−10	10
Deviation in feed balance protein stable period (%)	4.0	−5	20
Nitrogen (N) soil losses (kg ha^{-1})	38.5	20	–
Phosphorus (P) balance (kg ha^{-1})	7.5	0	–
Potassium (K) balance (kg ha^{-1})	0.9	0	–
Deviation bedding balance (%)	−7.4	−10	10
Amount of milk produced (quotum; kg)	610,280	0	650,000

can be reduced in this scenario because of a decreased labor demand for milking, which is directly dependent on the number of milk cows.

The general trends in the extremes in Table 3 suggested that aiming for a higher efficiency of the herd by reducing the number of animals (milk cows and replacement) and at the same time increasing milk production per cow appeared an appropriate strategy to improve the overall performance of the farming system. Another general trend was the increase in cropped areas of celeriac, chicory and sugar beets. Cropping of red beet and fodder beet was reduced in most solutions due to higher labor demands and lower revenues than other crops. Thus, from the optimization results suggested primary focus points for farming system reconfiguration.

5. Discussion

5.1. Bio-economic modeling and optimization

Farmers adjust their farming systems in an evolutionary manner for various reasons: (i) to be able to deal with the complexity of the farming system, which comprises many components and biological processes that are subject to variation due to fluctuating environmental circumstances, (ii) to address various objectives, constraints and opportunities that are relevant to the farmer and his enterprise, and (iii) to anticipate and respond to the continuously changing socio-institutional environment, that imposes new rules and regulations. Bio-economic farm models like FarmDESIGN have the potential to support the structuring of information to provide insight into consequences of adjustments to the configuration of farming systems, thus contributing to meaning and knowledge (Thornton and Herrero, 2001). Thus, farmers and their advisors could arrive at a clearer overview and understanding of the functioning of agroecosystems, with their many components and interacting processes. Models such as FarmDESIGN can serve as tools to support the evolutionary adaptation process that involves continuous learning by first creating a variety of options to choose from followed by informed selection of the most suitable alternative (Rossing et al., 2007; Janssen and van Ittersum, 2007; Groot and Rossing, 2011).

In multi-objective optimization, the Pareto-based ranking approach offers a powerful means for the combined evaluation of objectives without a priori weighing, which has scarcely been used thus far (Groot and Rossing, 2011). The original farm configuration provided crucial extra information for the Pareto ranking procedure to allow targeted exploration of the solution space when compared to random searches in the solution space (Figs. 4 and 5). When used as a starting point for the optimization and as a reference point for generated alternatives in the global improvement ranking scheme (Fig. 3) the original farm configuration enabled more effective and concentrated search in the most interesting part of the solution space, where alternatives performed better than the original farming system in all objectives (Fig. 5). However, there is also a potential risk when taking the original configuration as a starting point. This approach could promote lock-in onto a limited section of the solution space with alternatives that are rather similar to the original, and limit the probability of finding more revolutionary but still attainable alternatives for the farming system. This risk of lock-in seems acceptable when the approach is combined with a full exploration of the solution space to establish the trade-offs and synergies among farm performance indicators, which results in exploration of a large range of solution space explored (Fig. 4).

The solutions that performed best for the individual objectives were used to assess the contribution of changes in individual decision variables to farming system performance (Δ, expressed in% change in the desired direction, presented in Table 3). This procedure was appropriate since most decision variables represented linear changes in crop areas and destinations of crop products without interactions with other farm configuration decisions. An exception was the interaction between changes in cow number and milk yield per cow, which caused aggregated changes (sum of Δ values) in performance of >100%. This positive interaction can be explained from the fact that in the largest profit solution the greater milk production is combined with a smaller number of animals, whereas in the stepwise evaluation of individual changes this interaction is not taken into account; the greater milk production is combined with the original large animal number. Moreover, it should be noted that after the changes in areas and crop product destinations during the stepwise evaluation in some cases model constraints were not met, for instance regarding feed balances when amounts of animal feeds or levels of animal production were changed. Nevertheless, this procedure provided additional insight in the most relevant changes to achieve a selected objective.

Table 3

Characteristics of 10 solutions near the extremes (minima or maxima) of the four objectives. Values displayed concern objectives and decision variables for cultivated crops, destination of crop products and animal production on the Ter Linde farm. Averages were calculated for sets of 10 solutions that perform best for one of the objectives; the solutions perform better than the current situation in all the objectives. Δ% indicates the relative contribution of changes in values of decision variables to attaining improvements in various objectives. These were calculated as the change resulting from single variable changes over the range of improvement (best minus original performance for the given objective). *Note*: percentages do not add up to 100% due to interactions between animal number and milk production, and crop area and total farm area. Changes in the distribution of feed between grazing and stable seasons have no effect on objectives values and Δ% have been excluded from the table.

Category	Variable	Original	Highest profit		Highest SOM balance		Lowest soil N loss		Lowest labor balance	
			Value	Δ (%)	Value	Δ (%)	Value	Δ (%)	Value	Δ (%)
Objectives	Operating profit (€)	29,481	75,216		34,675		33,843		30,588	
	OM balance (kg ha^{-1})	−189	−185		309		−56		123	
	Soil N losses (kg ha^{-1})	40	29		40		20		32	
	Labor balance (h)	1698	1492		1561		1069		915	
Area of crops in rotations (ha)	Whole crop silage 1 (WCS)	5.0	5.3	−0.7	5.9	1.0	3.7	−3.2	3.4	2.0
	Celeriac	4.5	5.9	7.8	3.1	3.0	5.7	5.5	5.9	−1.7
	Sugar beet	3.0	5.0	4.8	4.9	−2.5	5.0	12.7	5.1	−3.0
	Fodder beet	1.0	0.2	5.7	0.4	0.5	2.9	4.5	0.4	0.9
	Maize silage	0.0	0.0	−0.1	0.0	0.0	0.0	0.1	0.0	0.0
	Grass clover 1 (grazing)	20.0	16.8	6.9	16.2	2.0	14.5	9.4	16.8	4.1
	Chicory	3.0	7.1	21.8	4.3	−3.1	7.1	19.1	7.0	−10.3
	Celeriac	6.5	7.5	5.4	7.2	−1.6	7.4	4.1	7.4	−1.2
	Red beet	2.0	0.1	−4.3	0.9	2.5	0.3	−12.7	0.2	7.0
	Sugar beet	1.5	2.0	1.2	2.2	−1.0	2.5	6.4	2.4	−1.2
	Potatoes	4.0	4.5	3.6	4.3	−0.6	4.4	2.6	4.4	−1.6
	Potatoes and green manure (GM)	2.5	2.9	3.1	2.8	−0.3	2.6	0.7	2.5	0.1
	Black beans	4.0	3.8	−0.7	0.2	9.6	6.5	−0.2	6.7	−3.5
	Black beans and GM	2.5	0.2	−8.1	0.3	2.9	0.1	4.0	0.1	4.8
	Pumpkin	4.0	6.4	16.3	0.3	10.3	6.5	11.6	0.4	21.2
	Pumpkin and GM	2.5	1.0	−9.7	5.9	−5.1	0.5	−6.7	0.3	13.9
	Grass clover 2 (mowing)	13.0	9.9	6.2	14.8	1.3	5.6	57.7	11.1	1.2
	Grass clover 3 (grazing)	1.2	2.7	−0.3	2.6	0.0	2.8	0.3	2.8	−0.1
	Grass clover 4 (extensive use)	2.5	2.7	1.4	3.0	0.0	2.8	−0.9	2.7	0.2
Crop products used as feed (Mg DM)	Beet pulp	70	51	8.0	65	−0.6	37	21.1	37	0.0
	Grass clover silage 1	40	67	−8.9	35	−0.9	38	2.2	18	0.0
	Concentrate	66	65	1.0	47	−3.0	67	−0.7	69	0.0
Fraction of feed used in stable period	Beet pulp	0.20	0.20		0.20		0.20		0.20	
	Grass clover silage 1	1.00	0.97		0.96		0.97		0.96	
	Concentrate	1.00	0.99		0.99		0.99		0.99	
	Fodder beet	1.00	0.95		0.96		0.96		0.94	
	WCS Silage	0.00	0.15		0.16		0.31		0.24	
	Grass clover silage 2	1.00	0.97		0.96		0.98		0.97	
	Hay	1.00	0.92		0.94		0.94		0.96	
Bedding (Mg DM)	Straw	125	146	−6.5	250	80.9	213	−24.0	237	0.0
Milk cows	Number	76	69	−47.2	76	−0.1	55	−32.3	59	59.5
	Milk production (kg day^{-1})	22.0	25.8	103.4	23.4	0.0	27.2	24.8	27.3	0.0
	Replacement rate (per year)	0.15	0.10	−0.4	0.10	0.7	0.10	−0.3	0.10	7.7
	Bedding supplied (kg day^{-1})	4.0	5.5	0.0	8.8	0.0	9.6	0.0	9.6	0.0

The underlined values contribute for 10% or move to the improvement of the performance of objectives.

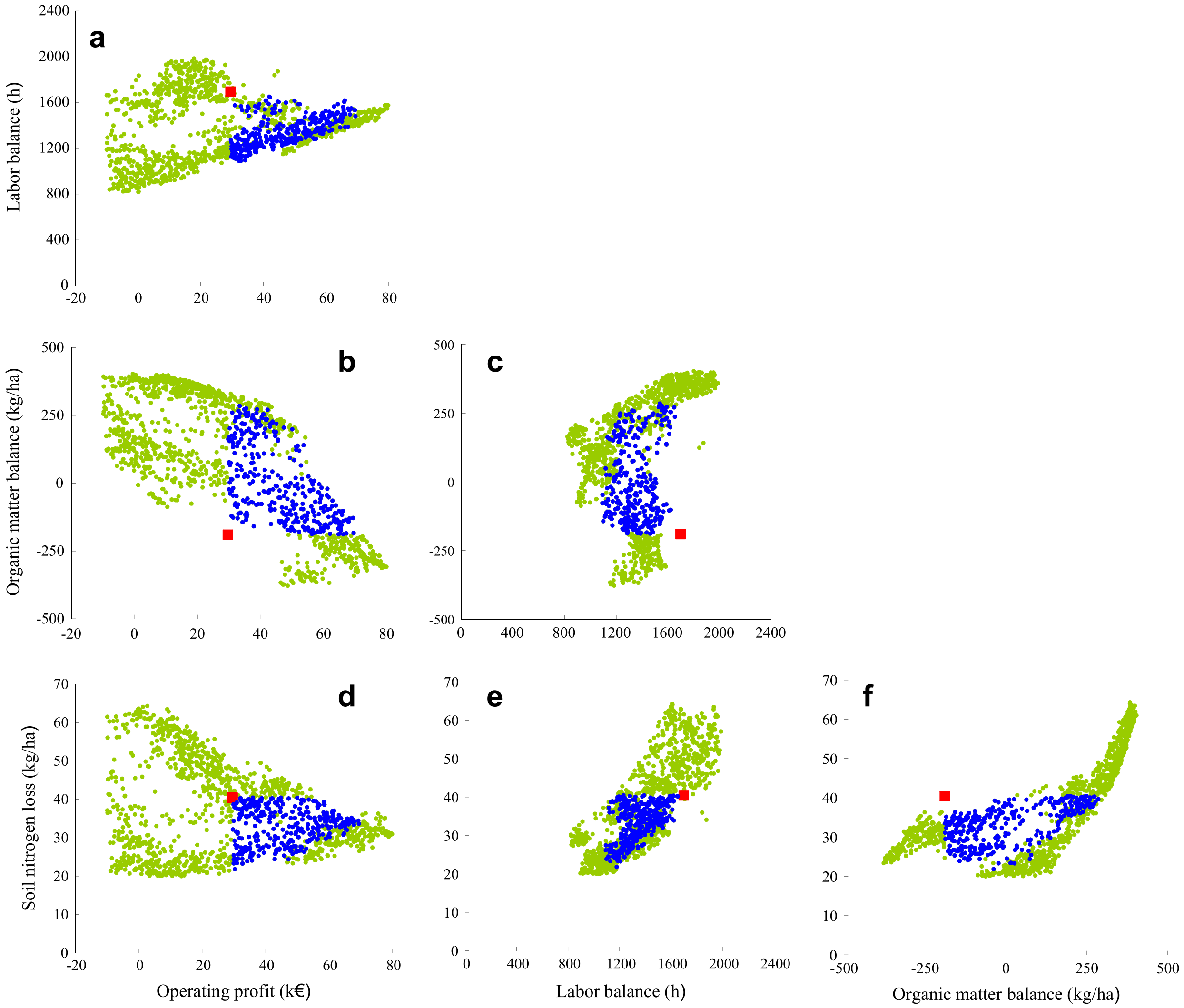

Fig. 4. Relations between farm performance indicators as represented by Pareto frontiers after multi-objective optimization using the Goldberg (1989) ranking scheme for full exploration of the frontier trade-off frontier. Each dot represents a farming system configuration, green for Pareto rank 1 solutions, blue for solutions that outperform the original solution in all objectives. The red square represents the original farming system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.2. Validation

Models and indicators can be evaluated in terms of design-, output- and end-user validity (Bockstaller and Girardin, 2003). Design validation addresses the scientific soundness of the model calculations. A major issue for design validation is the selection of the correct combination of algorithms that have to perform calculation procedures for a diverse set of indicators relating to environmental, economic and social aspects of the farming system. The calculations in the model are primarily annual balance calculations and aggregations based on on-farm collected data. Other calculations concerning the feed balance, manure degradation, nutrient losses from manure, and soil organic matter breakdown are based on algorithms that are founded on existing and accepted scientific approaches.

Output validation is concerned with the question whether the model produces realistic and reliable results, which can be evaluated for instance by comparison with measured data. In the case of the FarmDESIGN model output validation is to a large degree straightforward, since carbon and nutrient balances and flows are directly derived from measured or estimated quantities of carbon and nutrients in farm components and materials imported into or exported from the farm. Economic and labor balance calculations only use reported costs, prices and labor inputs. The uncertainties in outputs of the model reside in the quality of the input data and in the calculations of feed balance, manure degradation, nutrient losses from manure, and soil organic matter breakdown. The parameterization of these algorithms is difficult, in particular in an on-farm setting, so that output validation will depend on assessments based on expert knowledge, as performed in this case by a farm advisor and the farmers based on their administrative records.

Defining a farm in the model and evaluating modeling results typically requires two to three sessions of a few hours with the farmer. In-between sessions the researchers or advisors parameterize and run the optimization algorithm. Information additional to that provided by the graphical user interface may be generated, such as the Δ values. This iterative process can be embedded in consecutive adaptive learning and design cycles (Groot and Rossing, 2011), in which all modeling steps are repeated, for instance annually, so that changes in on-farm conditions and external influences such as prices and policies can be included in a continuous farm improvement process.

We performed end-user validation by discussing model results with the farmers, for both the analysis of the current situation and

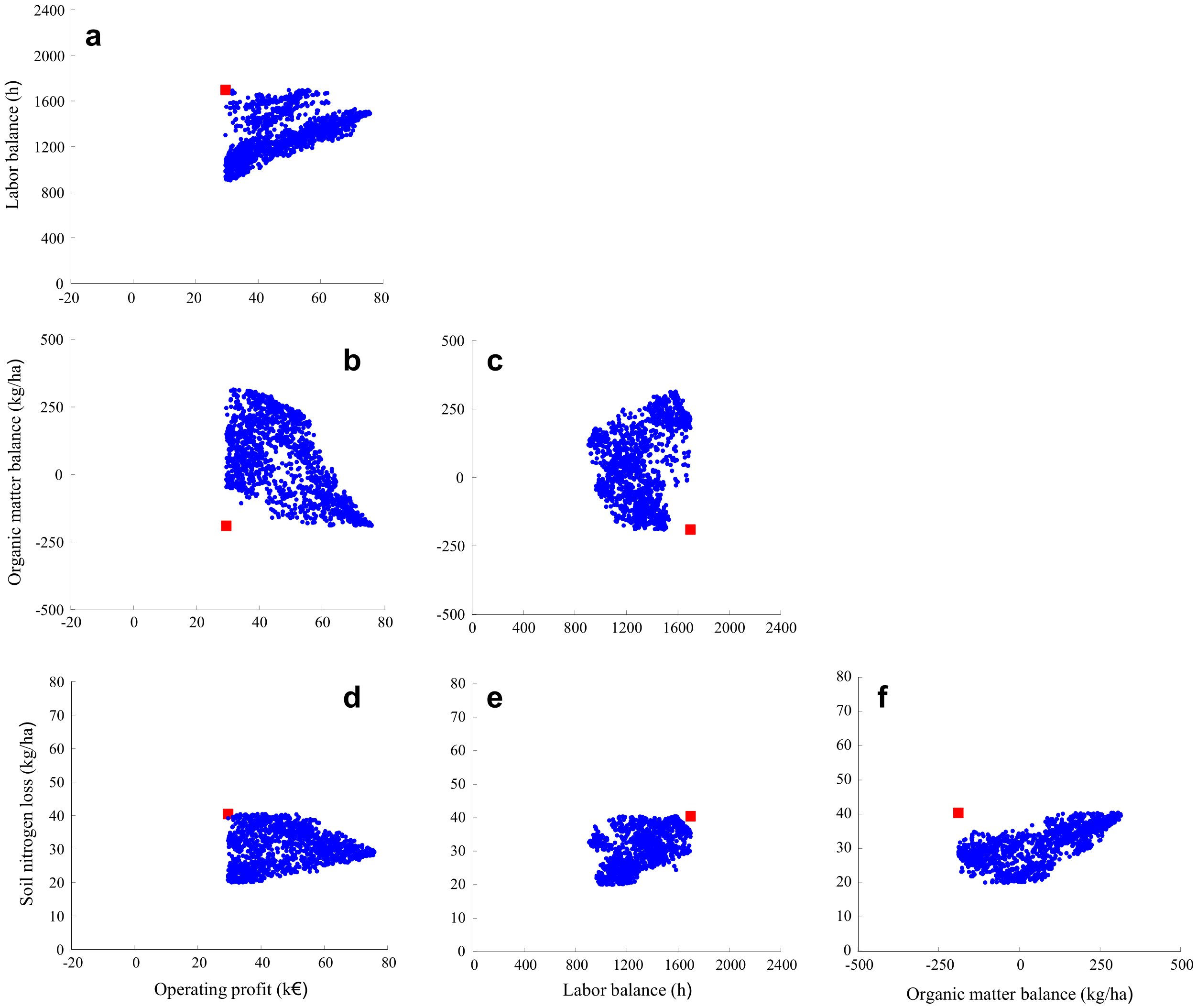

Fig. 5. Relations between farm performance indicators as represented by Pareto frontiers after multi-objective optimization using the adjusted ranking scheme by assigning rank 0 to solutions that outperform the original solution in all objectives. Each dot represents a farming system configuration. The red square represents the original farming system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the optimization results. The analysis of the current situation on the farm highlighted some points of attention that were recognized by the farmers. The regular labor balance was strongly positive, indicating that additional labor should be hired. The farmers acknowledged the need to attract additional farm workers, but indicated that it was difficult to recruit skilled personnel. Additionally, the farmers were concerned about the negative soil organic matter balance, and had experimented in the past with options to improve the OM balance without success. The soil losses of N and volatilization losses were not extremely high, but the farmers were interested to explore options for improvement. The results of the optimization yielded some new and useful ideas to reach improvements for organic matter balance and reduction of losses, although also some additional constraints were identified, for instance in obtaining sufficient amounts of bedding material. The need to improve the animal gross margin was recognized by the farmers, and strengthening the animal husbandry part of the farm recently has received special focus by increasing animal numbers, milk production per animal and revenues per unit of product. Increasing the production per animal necessitates development of integral approaches involving animal breeding and selection, and better nutrition and health status, and will demand a considerable investment period and effort from the farmers.

5.3. Trade-offs in modeling

In modeling we search for a balance between the level of detail, the precision required, the model's flexibility and the data requirements (Brooks and Tobias, 1996; Thornton and Herrero, 2001; Astrup et al., 2008). More detailed insight into spatial and temporal aspects of the farming system could potentially improve understanding of long-term impacts and feedbacks, for instance between soil fertility and crop productivity. Although recently some relatively simple dynamic modeling approaches for on-farm application have become available for herd management (Rufino et al., 2009) and soil organic matter dynamics (Tittonell et al., 2007a, 2007b; Saffih-Hdadi and Mary, 2008; Kemanian and Stöckle, 2010), incorporation of such models or modules would certainly increase the required number of parameters and calculation time. The effects of uncertainty in model inputs on the optimization outcomes could be evaluated with available algorithms that support multi-objective optimization under uncertainty (Choi et al., 2008; Crespo et al., 2010).

Various modeling approaches for mixed crop-livestock farms have been developed during the last years (Gouttenoire et al., 2011). Some of these tools focus on the dynamics of the biological processes (continuous dynamic modeling), the farm management (discrete event modeling) and optimization (linear programming). These models are frequently constructed and applied in participatory settings with farmers in both developed and developing parts of the world (e.g., Amede and Delve, 2008; Behera et al., 2008; Cabrera et al., 2007; Le Gal et al., 2010). On-farm action research with models is often faced with the challenge to keep model functioning and outputs transparent and relevant to the stakeholders that are involved (Sterk et al., 2006; Andrieu and Nogueira, 2010). In the current application of the FarmDESIGN model in on-farm redesign and during teaching of our courses on analysis and design of mixed farming systems, the end-users of the model are farmers (and their advisors) and students. Recent experiences of application of the model have resulted in appreciation from both user groups, after a considerable development period in which the model was improved in an iterative process. The current user interface strongly supported acceptance of the model by the end-users.

6. Conclusions

The FarmDESIGN model proved to be effective in representing the complex mixed organic farming system that was selected for this study; it supported the analysis of problems in the original farm configuration and indicated avenues for adjustments of the configuration to improve farm performance in terms of various objectives. Other experiences with the model in an arid region in Mexico (Flores-Sanchez et al., 2011) and in student projects in Uruguay, Nepal and India indicate that it is generic enough to accommodate farming systems in environments that are contrasting in bio-physical conditions, farming systems configurations and data availability. Desirable extensions of the model include a water balance, accounting for the added value generated by processing of crop and animal products, and incorporating erosion explicitly in the model. We conclude that this approach to multi-objective optimization linked to bio-economic farm models can play an important role in the design of mixed farming systems and has a strong potential to support the learning and decision-making processes of farmers, farm advisers and scientists.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2012.03.012.

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