Agricultural Systems xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Trade-offs in soil fertility management on arable farms

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ARTICLE INFO

Article history:
Received 22 November 2015
Received in revised form 11 September 2016
Accepted 17 September 2016
Available online xxxx

Keywords:
carbon sequestration
nitrogen losses
greenhouse gases
climate change mitigation
linear programming

ABSTRACT

Crop production and soil fertility management implies a multitude of decisions and activities on crop choice, rotation design and nutrient management. In practice, the choices to be made and the resulting outcomes are subject to a wide range of objectives and constraints. Objectives are economic as well as environmental, for instance sequestering carbon in agricultural soils or reducing nitrogen losses. Constraints originate from biophysical and institutional conditions that may restrict the possibilities for choosing crops or using specific cultivation and fertilization practices. To explore the consequences of management interventions to increase the supply of organic C to the soil on income and N losses, we developed the linear programming model NutMatch. The novelty of the model is the coherent description of mutual interdependencies amongst a broad range of sustainability indicators related to soil fertility management in arable cropping, enabling the quantification of synergies and trade-offs between objectives. NutMatch was applied to four different crop rotations subjected to four fertiliser strategies differing in the use of the organic fertilisers cattle slurry, pig slurry or compost, next to mineral fertiliser. Each combination of rotation and fertiliser strategy contributed differently to financial return, N emissions and organic matter inputs into the soil.

Our model calculations show that, at the rotational level, crop residues, cattle slurry and compost each substantially contributed to SOC accumulation (range 200-450 kg C ha^{-1} yr^{-1}), while contributions of pig slurry and cover crops were small (20-50 kg C ha^{-1} yr^{-1}). The use of compost and pig slurry resulted in increases of 0.61-0.73 and 3.15-3.38 kg N_2O-N per 100 kg extra SOC accumulated, respectively, with the other fertilizers taking an intermediate position. From a GHG emission perspective, the maximum acceptable increase is 0.75 kg N_2O-N per 100 kg extra SOC accumulated, which was only met by compost. Doubling the winter wheat area combined with the cultivation of cover crops to increase SOC accumulation resulted in a net GHG emission benefit, but was associated with a financial trade-off of 2.30-3.30 euro per kg SOC gained.

Our model calculations suggest that trade-offs between C inputs and emissions of greenhouse gases (notably N_2O) or other pollutants (NO_3, NH_3) can be substantial. Due to the many data from a large variety of sources incorporated in the model, the trade-offs are uncertain. Our model-based explorations provide insight in soil carbon sequestration options and their limitations vis-a-vis other objectives.

1. Introduction

The amount and quality of soil organic carbon (SOC) is often used as indicator of soil quality and productivity (Amundson et al., 2015; Powlson et al., 2011a). At the global scale, agricultural soils constitute a large C pool in the form of soil organic matter, and there is thus scope for large amounts of C to be lost or gained from soils as a consequence of farming practices (Smith, 2012). Management of arable land through repeated disturbance has turned many arable soils into C sources (Lal et al., 2007), contributing to climate change. Increased awareness of climate change and concerns about soil quality decline have led to increased emphasis on sequestering C in the soil: increasing SOC content is often seen as a desirable objective. Strategies to increase SOC content in crop rotations include cover crop cultivation (Poeplau & Don, 2015), nutrient and crop residue management (Lehtinen et al., 2014; Blair et al., 2006), application of manures and composts (Triberti et al., 2008) and no- or minimum-till farming (e.g. Powlson et al., 2014), with the latter a much debated option. While there are many advantages to increasing soil C stocks, there are a number of issues associated with soil C sequestration which make it a risky climate change mitigation option (Smith, 2012; Powlson et al., 2011b). These issues include the finiteness of the amount of C that can be stored in the soil, the reversibility of C sequestration, and a number of 'leakage' and pollution swapping issues. Despite these limitations, soil C sequestration may have a role in reducing the short term atmospheric CO_2

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http://dx.doi.org/10.1016/j.agsy.2016.09.013
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concentration, thus buying time to develop longer term emission reduction solutions across all sectors of the economy (Smith, 2012).

Besides of CO_2, agricultural soils are also a source of nitrous oxide (N_2O) (Reay et al., 2012). Nitrous oxide is emitted largely during microbially governed transformation processes of soil-N, derived from crop residues and the application of inorganic and organic fertilizers. In developed, high-input agriculture, the N taken up by crops is typically no more than 60 per cent of that applied (Lassaletta et al., 2014; Janzen et al., 2003). The remainder is lost in various forms, with major environmental impacts such as high nitrate levels in drinking water aquifers and eutrophication of surface waters. Reducing N input is an important strategy in ameliorating the effect of arable crop production on N_2O emission and water quality (Hillier et al., 2009), but may have a penalty in terms of (economic) productivity.

Crop production and related soil management implies a multitude of decisions and activities on soil tillage, crop choice, rotation design, nutrient supply, water supply and crop protection. Within each of these management categories, many options are usually available to farmers, and the choices to be made and the resulting outcomes are subject to a wide range of economic and environmental objectives and constraints (Hengsdijk & van Ittersum, 2002; Groot et al., 2012). Finding ways to maintain farm profitability while reducing undesirable emissions or maintaining carbon stocks is complicated by interactions and feedbacks among agricultural practices. For example, the addition of organic materials to the soil, such as animal manures and composts, potentially increases SOC content, and increased yields resulting from fertiliser application can result in increased crop residue additions to the soil organic matter pool (Blair et al., 2006). However, large additions of mineral and organic fertilisers to the soil may enhance nitrogen losses to water and atmosphere or result in phosphorus saturation of agricultural soils. These and other examples illustrate the existence of conflicts or trade-offs between objectives of soil management (Powlson et al., 2011a). Given the complexity of interactions and conflicts, the selection of management options that result in a maximization of the net benefits from agriculture is no easy task.

Hengsdijk & van Ittersum (2003) presented an agro-ecological modelling approach, converting information on specific aims for agricultural systems into targeted identification and quantification of land use systems and their management options. In the approach, process based knowledge and empirical data regarding agronomic relationships are integrated and synthesised, using a variety of numerical tools, while taking into account available resources and prevailing land-related objectives (ten Berge et al., 2000). Typically, such 'engineered' land use systems are expressed in terms of inputs and outputs, including production, environmental and socio-economic characteristics. At relatively low costs and risks, agro-ecological modelling of land use systems enables the systematic exploration of land use options at farm and regional scales that are difficult to monitor otherwise. Such model-based land use systems hence provide a framework to disentangle the complex relationships between agricultural production, environment and economy and to explicate synergies and trade-offs between different goal variables, contributing to informed decision making with respect to future land use or research priorities. Currently, many descriptions and applications of such model studies exist (Janssen & van Ittersum, 2007), but to our knowledge no model is available that provides the required detail in nutrient management at farm level to reveal trade-offs resulting from soil fertility management. The purpose of this paper is to show how the NutMatch model can support multi-criteria decision making in nutrient and soil fertility management. To this end, the model is deployed for ex-ante assessments of choices in soil fertility management in arable farming in the Netherlands, illustrating long term consequences of these choices on farm income, nitrogen losses and the build-up of soil organic matter.

In the next section we present the linear programming (LP) model NutMatch. The novelty of this model is the coherent description of mutual interdependencies amongst a broad range of sustainability indicators related to crop production, soil fertility management, SOC content, N emissions and farm economics, enabling the quantification of synergies and trade-offs between objectives. NutMatch differs from most other modelling efforts related to soil fertility management in that it is a static optimization model that can be used for integrating several sustainability aspects within a whole farming system context. This can be contrasted with dynamic, process-oriented simulation models used for predicting nitrogen and soil fertility dynamics at the plot or higher scales in response to changed climate, management or land use (e.g. Ryals et al., 2015; Lugato et al., 2014; Viaud et al., 2010; Batlle-Aguilar et al., 2010), that lack the capacity to handle a range of objectives simultaneously.

2. Materials and Methods

2.1. Case study

The NutMatch model was applied to arable farming on sandy soils in the Netherlands. Here, arable farming is characterized by high intensity, expressed in the adoption of crop rotations with a large share of high-value crops (potatoes, vegetables) and the use of relatively high levels of external inputs such as pesticides and fertilisers. The use of organic and mineral fertilisers on arable farms is currently ceiled by legally binding maximum nitrogen and phosphorus application standards defined at the crop level (Schröder & Neeteson, 2008). Due to the ample supply of animal slurries in the Netherlands, suppliers pay arable farmers for using animal slurries in crop fertilisation. Therefore, arable farmers tend to import a large part of the maximum allowable phosphorus application (28.4 kg P or 65 kg P_2O_5 ha^{-1} yr^{-1} in 2014) as phosphorus in animal slurries.

Arable farmers are concerned that restrictions on the use of organic and mineral fertilizers will in the long term reduce soil fertility, jeopardizing quality production and economic profits (ten Berge et al., 2010, Reijneveld et al., 2009). While no general decline in soil fertility has been documented for the Netherlands as yet (Reijneveld et al., 2009), it is recognized that past management has resulted in high levels of soil fertility indicators such as SOC content, soil N supply and phosphorus status. Although Nitrates Directive regulations have resulted in reduced fertiliser inputs over time, nitrate leaching from agriculture still poses a serious problem, with nitrate concentrations in shallow groundwater under arable farming among the highest in the country. About seventy percent of arable farms on sandy soils have until now not been able to meet the EU target for shallow groundwater of 11.3 mg NO_3-N per litre (RIVM, 2012). Since 2000, average nitrate concentrations on arable farms in the sandy region (covering the southeast, east and northeast of the Netherlands, i.e. about half the agricultural area in the Netherlands), have varied from about 13.6 mg per litre to 19.2 mg NO_3-N per litre, with no clear trend.

2.2. Rotation and nutrient management variants

Based on the above regional context, arable cropping systems in NutMatch were described according to so-called design criteria (Hengsdijk & van Ittersum, 2003), each represented by a number of variants. Our design criteria were the composition of the rotation, nutrient sources used, and the level of N supply to individual crops relative to their full N demand at economically optimal N rate (Table 1). We defined four crop rotations differing in the relative areas of winter wheat, ware potato, sugar beet and silage maize, and differing in the use or not of a cover crop after winter wheat. The four rotations obviously have different nutrient requirements, financial returns and inputs of crop residues into the soil, affecting SOC and soil N dynamics. Of the crops considered, ware potato is the single most important crop in farm economic terms (see Supplementary Material). The crop with the largest crop residue input is winter wheat, with straw assumed to be incorporated into the soil. Cover crops after winter wheat bring