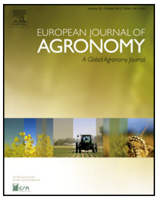
Europ. J. Agronomy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

European Journal of Agronomy

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



A cropping system assessment framework—Evaluating effects of introducing legumes into crop rotations

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ARTICLE INFO

Article history:
Received 6 May 2015
Received in revised form 3 November 2015
Accepted 5 November 2015
Available online xxx

Keywords:
Expert knowledge
Land use change impacts
Multi-criteria
Protein crops
Resource-efficiency
Rotation generator

ABSTRACT

Methods are needed for the design and evaluation of cropping systems, in order to test the effects of introducing or reintroducing crops into rotations. The interaction of legumes with other crops (rotational effects) requires an assessment at the cropping system scale. The objective of this work is to introduce a cropping system framework to assess the impacts of changes in cropping systems in a participatory approach with experts, i.e., the integration of legumes into crop rotations and to demonstrate its application in two case studies. The framework consists of a rule-based rotation generator and a set of algorithms to calculate impact indicators. It follows a three-step approach: (i) generate rotations, (ii) evaluate crop production activities using environmental, economic and phytosanitary indicators, and (iii) design cropping systems and assess their impacts. Experienced agronomists and environmental scientists were involved at several stages of the framework development and testing in order to ensure the practicability of designed cropping systems. The framework was tested in Västra Götaland (Sweden) and Brandenburg (Germany) by comparing cropping systems with and without legumes. In both case studies, cropping systems with legumes reduced nitrous oxide emissions with comparable or slightly lower nitrate-N leaching, and had positive phytosanitary effects. In arable systems with grain legumes, gross margins were lower than in cropping systems without legumes despite taking pre-crop effects into account. Forage cropping systems with legumes had higher or equivalent gross margins and at the same time higher environmental benefits than cropping systems without legumes. The framework supports agronomists to design sustainable legume-supported cropping systems and to assess their impacts.

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1. Introduction

Given the negative side-effects of many current agricultural practices, along with changes in both climate and international trade conditions, novel and resource-efficient production methods are needed. In Europe, less than 30% of the plant-based protein supplement fed to livestock is produced within the continent (Bouxin, 2014; Bues et al., 2013). Moreover, rotations have become very narrow and their sustainability is often questioned (Tilman et al., 2002). In order to design more sustainable cropping systems, new methods are required.

Interactions between crops are an important component of how changes in cropping systems impact on their agro-economic and environmental performance. Fertilization, nitrogen mineralization, nitrate leaching, greenhouse-gas emissions, infestations with pests, diseases and weeds, and eventual crop yield are all affected not only by the management of the individual crops but also by long-term processes that are influenced by crop sequence (Bachinger and Zander, 2007; Detlefsen and Jensen, 2007; Dogliotti et al., 2003). Thus an assessment framework is needed that considers rotational effects and systematically compares existing with novel cropping

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http://dx.doi.org/10.1016/j.eja.2015.11.005
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Please cite this article in press as: Reckling, M., et al., A cropping system assessment framework—Evaluating effects of introducing legumes into crop rotations. Eur. J. Agron. (2015), http://dx.doi.org/10.1016/j.eja.2015.11.005

systems. Such a framework is especially needed when studying the impacts of legumes, because of their diverse impacts on cropping systems (Jensen et al., 2011; Köpke and Nemecek, 2010; Peoples et al., 2009).

Many studies have quantified rotational effects (often called pre-crop, break crop or residual effects) (see Angus et al. (2015) and Preissel et al. (2015) for recent reviews). Under European conditions, grain legume pre-crop effects are variable and increasing cereal yields by 0.5–1.6 Mg ha^{-1} Preissel et al. (2015). According to the meta-analysis by Preissel et al. (2015), the pre-crop effect of grain legumes is highest under low N fertilization to subsequent crops and comparable to non-leguminous oilseed crops.

Legume production has declined in most of Europe, from 5.8 M ha in 1961 (4.7% of arable land) to 1.8 M ha in 2013 (1.6%) (FAOstat, 2015). There are many reasons why farmers do not grow legumes, including specialization in cereal crop production, low and unstable yields (Cernay et al., 2015; Reckling et al., 2015b), and of low gross margins (Preissel et al., 2015), low and unpredictable policy support (Bues et al., 2013), and inability to recognize or evaluate the long-term benefits of legumes within cropping systems (Preissel et al., 2015). While the effect of legumes on yield of the following crop is easily measured, changes in root growth and pressures from pests and pathogens are harder to quantify. Legumes generally have lower gross margins than cereals or oilseeds, but their rotational effects increase the gross margins of subsequent crops, so assessment of legumes needs to be performed at the cropping system scale (Preissel et al., 2015) using crop rotations as the starting point. Furthermore, supply chains and markets are inadequately developed for most legume crops as shown for France by Meynard et al. (2013) except for soybean, for which the global market is well developed. Soybean areas in Europe are limited by climatic constraints, but there is considerable potential for development (de Visser et al., 2014). New varieties have been developed that are also promising under cool growing conditions (Zimmer et al., 2016).

We define a crop rotation according to Castellazzi et al. (2008) as a sequence of crops that is *fixed* (each crop follows a pre-defined order), *cyclical* (in that it repeats itself) and has a *fixed length*. The cropping system comprises the rotation, management activities (tillage, inputs, harvesting etc.) and production orientation (arable, mixed or forage). The crop rotation is considered as the starting point in cropping system analysis (Vereijken, 1997).

Bergez et al. (2010) proposed a four-step process to design cropping systems: (a) generation, (b) simulation, (c) evaluation, and d) comparison and choice. The *generation* of cropping systems and rotations can be based on existing cropping patterns, using (i) pure statistical data such as that from the integrated administration and control system (IACS) (Steinmann and Dobers, 2013), (ii) statistical data combined with rules on crop sequences (Lorenz et al., 2013; Schönhart et al., 2011), and (iii) statistical data and mathematical frameworks (Castellazzi et al., 2008; Detlefsen and Jensen, 2007). Statistical data represent current farming trends that are influenced by current policy and market drivers, but do not allow the design of cropping systems using niche or novel crops such as legumes. For this purpose another approach is required. Rule-based models are useful ways to generate novel systems (Bachinger and Zander, 2007; Dogliotti et al., 2003; Naudin et al., 2015), as they employ expert knowledge where no formal empirical data are available.

For specific, localized case studies, cropping system assessments have been conducted through *simulation* with dynamic models. Their advantage is to model soil–crop processes in detail and to simulate scenarios such as those expected under climate change. Nevertheless, they cannot be employed widely, due to their high data requirements, and they do not generate novel systems. Furthermore, crop rotations receive little consideration in dynamic models, as they are often used to assess single crops separately year-by-year not taking pre-crop effects into account (Lorenz et al., 2013). In a comparison of European crop models, Kollas et al. (2015) showed that modelling crop rotations achieves more robust results than modelling single crops, and revealed several constraints to modelling rotational effects. While most dynamic models cover soil water-related effects along with the carry-over of carbon and nitrogen in residues below and above ground, few account for crop residue quality and decomposition characteristics (Rahn et al., 2010) or the impacts on biological N fixation (BNF) of legumes and its consequences for subsequent crops. None of the models is therefore suitable for our assessment because (i) they do not generate rotations, (ii) they cannot process numerous rotations, (iii) few include carry-over effects, (iv) few model perennial crops, such as temporary grassland, (v) none incorporates soil structure effects such as soil compaction (C. Nendel Personal Communication) or break-crop effects on pests, diseases and weeds (Bergez et al., 2010), and (vi) all require detailed calibration data that is seldom available. Hence, these dynamic models are available for only a few specific case studies.

A static and rule-based approach for the *evaluation* of cropping systems without *simulation* allows a large-scale application by dealing with some of these disadvantages. (i) It makes explicit the knowledge of agronomists through the formalization of rules, (ii) requires less input data, thus allowing the inclusion of many different crops including perennials, and (iii) combines crop rotation generation and evaluation. These advantages come at the cost of less detailed results, and soil–crop processes are considered on only an annual basis. The static nature of the model means that changes in climate or management need to be implemented manually. The input of experts is required to formulate production activities and to check the plausibility of results.

The *comparison and choice* of cropping systems in the design process can be supported by multi-criteria methods (Carof et al., 2013) as shown for the design of legume-supported cropping systems in Europe (Reckling et al., 2015a).

Hence, we set out to develop a cropping system assessment framework following the process proposed by Bergez et al. (2010), excluding the simulation step, and using a static and rule-based approach considering crop rotations and rotational effects. The framework was tested by evaluating the effects of legume crops on the sustainability of agriculture by comparing cropping systems with and without legumes in two European regions, Västra Götaland in Sweden and Brandenburg in Germany.

2. The assessment framework

2.1. General approach

The framework consists of a rule-based rotation generator that comprises a fixed set of rules at the crop and rotational level and a set of algorithms to calculate the impact indicators. The application of the framework to a specific region or problem follows a three-step approach (Fig. 1): (i) generate crop rotations, (ii) evaluate crop production activities (CPA) using environmental, economic and phytosanitary indicators, and (iii) design cropping systems by combining generated rotations with evaluated CPA, and assessing their impacts.

To apply the framework, experts play an essential role: (i) agronomists define input variables such as crops, restriction values for rotation generation, and CPA, and (ii) agronomists and environmental scientists check the plausibility of evaluation results, namely the list of generated rotations and the calculated impacts, and potentially revise input values. The involvement of experts in the evaluation process is explained in more detail in Section 2.6, "framework evaluation". These experts use information and knowl-

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