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Assessing the environmental impacts of cropping systems and cover crops: Life cycle assessment of FAST, a long-term arable farming field experiment

Ulrich E. Prechsl[a], Raphael Wittwer[a,b], Marcel G.A. van der Heijden[a,b,c], Gisela Lüscher[a], Philippe Jeanneret[a], Thomas Nemecek[a,*]

[a] *Agroscope, Research Division Agroecology and Environment, Reckenholzstrasse 191, 8046 Zurich, Switzerland*
[b] *Plant-Microbe-Interactions, Department of Biology, Utrecht University, 3508 TB Utrecht, The Netherlands*
[c] *Department of Evolutionary Biology and Environmental Studies, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*

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ABSTRACT

To reduce environmental impacts of cropping systems, various management strategies are being discussed. Long-term field experiments are particularly suitable to directly compare different management strategies and to perform a comprehensive impact assessment. To identify the key drivers of several environmental impacts, we analysed a six year crop rotation of the Farming System and Tillage Experiment (FAST) by means of the Swiss Agriculture Life Cycle Assessment method (SALCA). The following factors of the FAST experiment were considered: (1) cropping system (stockless conventional farming vs. organic farming), (2) tillage (intensive tillage vs. no or reduced tillage), and (3) cover crop. We analysed the effects of these three factors on the global warming potential (GWP), aquatic and terrestrial eutrophication, and aquatic ecotoxicity for two functional units, i.e. per product and per area. Potential impacts on biodiversity were also analysed. Our analysis revealed that there is not one superior cropping system, as the ranking depended on the environmental impact selected and on the functional unit. The cropping system had the strongest effect on most of the environmental impacts, and this was mainly driven by differences in N-fertilisation (amount and form) and yield. The global warming potential, for instance, was highest in both conventional systems compared to the organic systems, when emissions were calculated per area. In contrast, calculating emissions per product, there were no statistical differences between all four systems. On the other hand, due to higher nitrogen emissions related to the application of cattle slurry in the organic system, the terrestrial eutrophication of the organic systems was higher than the conventional systems, independent of the functional unit. The effects of tillage were much lower compared to the cropping system. No tillage, but not necessarily reduced tillage, and the cultivation of cover crops had the potential to reduce aquatic eutrophication. As N-fertilisation dominated many impact categories, we suggest improving the N-efficiency as a crucial leverage point to improve the environmental performance of arable farming systems.

1. Introduction

Agricultural production increased tremendously in the last decades (Tilman et al., 2002). However, agriculture also has negative impacts on the environment. Depending on the definition of the system boundaries, it is estimated that agriculture contributes between 13.5% and 30.0% to the total global anthropogenic greenhouse gas emissions (Bellarby et al., 2008; IPCC, 2007). Between 1961 and 2011, these emissions doubled, reflecting the pace of the continual agricultural intensification (FAOSTAT, 2014). Population growth, rising per capita caloric intake, changing dietary preferences, and limited resources, particularly agricultural land, are important drivers for the increasing intensification of the agricultural production and its emissions (Popp et al., 2010; Smith et al., 2007). Although animal husbandry is responsible for a vast amount of climate-relevant emissions (enteric CH_4), arable farming is particularly associated with volatile and aquatic nitrogen losses (Carpenter et al., 1998; Skinner et al., 1997). In fact, one of the most critical leverage points in agriculture is the excess of nitrogen in agricultural areas and associated N emissions (West et al., 2014). The excess of nitrogen is also responsible for the nutrient enrichment in terrestrial and, together with phosphorus, in aquatic ecosystems, the eutrophication, which can cause tremendous changes in the environmental conditions and thus species composition (Carpenter et al., 1998; Withers and Haygarth, 2007). Additionally, the land use and associated changes in natural habitats have a strong impact on the natural

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[*] Corresponding author.
E-mail address: thomas.nemecek@agroscope.admin.ch (T. Nemecek).

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flora and fauna. Agriculture is known to be a key driver for above- and belowground biodiversity loss (Butler et al., 2007; Green et al., 2005; Hails, 2002; Bender et al., 2016). Furthermore, numerous other detrimental impacts on the environment, such as soil erosion or the contamination with toxic pollutants are related to agriculture, especially to arable farming (Aktar et al., 2009; Carvalho, 2006; Skinner et al., 1997).

Considering the numerous potential impacts of arable farming and the necessity to produce enough food, the question arises: How could arable farming be optimised for the lowest possible impacts on the environment? To address this question, several strategies are currently discussed, for example the cultivation of cover crops and an improved nutrient management to increase the nutrient efficiency (Dalgaard et al., 2011; Smith et al., 2008; Smith et al., 2007). In Switzerland, for instance, efforts in nutrient management were successful and nitrogen excess could be reduced by about one-third between 1990 and 2013 (BFS, 2015). Further suggested management strategies are the expansion of organic farming systems or conservation agriculture (Gattinger et al., 2012; IPCC, 2007; Johnson et al., 2007; Khaledian et al., 2010; Smith et al., 2008). Numerous empirical studies were performed to test these different management strategies: The tillage regime, for instance, was often tested for its effects on agricultural parameters, such as soil properties, weed abundance and yield potential (De Vita et al., 2007; Gronle et al., 2015; Pittelkow et al., 2015; Vakali et al., 2011). As the "sustainability" i.e. the emission reduction became a central topic in research on agricultural management strategies, there are many studies focusing on environmental parameters, such as ammonia losses and greenhouse gas emissions (Bacenetti et al., 2015; Bacenetti et al., 2016; Carozzi et al., 2013; Fusi et al., 2014; Hokazono and Hayashi, 2012; Niero et al., 2015; Wang and Dalal, 2015). Most of these studies applied a Life Cycle Assessment, a method to assess emissions and resource use occurring from "cradle-to-grave" (Finkbeiner et al., 2006). However, it has also been shown that the environmental performance of a farming system strongly depends on the perspective of the analysis. Due to the lower yield in organic farming, the ecological advantage often diminishes dramatically if emissions are analysed per product unit (yield) instead of area unit (ha; Tuomisto et al., 2012). For that reason, the intensification of agriculture in terms of emissions relative to the yield has been also suggested as a cost-effective greenhouse gas mitigation strategy (Burney et al., 2010; Cassman, 1999).

These examples illustrate clearly that the uncertainties regarding the environmental performance of management strategies are still high and that site-specific and empirical long-term verifications are essential to overcome this problem. Moreover, studies testing multiple management strategy simultaneously and taking site-, crop-, and year-specific interactions into account are lacking. Therefore, the Farming System and Tillage Experiment (FAST), a long-term arable field experiment, was established in Switzerland. The FAST investigates mainly how several important agricultural indicators, such as productivity, plant nutrition, nutrient cycling, as well as plant and soil biodiversity and their ecosystem functions are affected by cropping system (stockless conventional vs. organic management), tillage (intensive tillage vs. no or reduced tillage), and cover crops (Wittwer et al., 2017). Moreover, this experiment aims at investigating the long-term environmental performance of the examined cropping systems. To consider multiple environmental impacts simultaneously, a Life Cycle Assessment (LCA) was performed, which has become an established tool to assess emissions from complex processes, such as agricultural production. LCA is a quantitative assessment of the main emissions occurring throughout the whole value chain, from 'cradle to grave'. Considered processes include resource extraction, production of primary materials and infrastructure, processing, transport, and storage. The sums of all occurring emissions and used resources (life cycle inventory) are summarised in impact categories, such as the global warming potential (GWP; Guinée, 2001; Hellweg and I Canals, 2014; ISO, 2006a), and are generally expressed as equivalents of one contributing substance (e.g. kg CO_2 equivalent).

To reveal the environmental impacts of the various management strategies of the FAST, we analysed the experiment with the Swiss Agriculture Life Cycle Assessment tool (SALCA). The central aim of this study was to evaluate and compare the environmental impacts of the three experimental factors of the FAST experiment over a six-year crop rotation from 2009 to 2015: (1) cropping system (stockless conventional farming vs. organic farming), (2) tillage, and (3) cover crops (compared with bare fallow). Through this analysis, we aimed at identifying the key drivers for individual emissions and thus the leverage points for ecological improvements in arable farming.

2. Materials and methods

2.1. Farming System and Tillage Experiment (FAST)

The FAST was established 2009 and is ongoing near the agricultural research institute Agroscope in Zurich-Reckenholz, Switzerland (latitude 47°26′N, longitude 8°31′E). General aims of this long-term experiment are to assess the agronomical performance, ecological services (e.g. plant and soil biodiversity and interactions, nutrient cycling, soil ecological functions), and economic viability of various production systems. Specific aims are a) a general comparison of four production systems of arable crops in Switzerland, b) the development of reduced tillage in organic farming, and c) assessing the role of cover crops in the examined systems (Wittwer et al., 2017). The three investigated factors with the corresponding factor levels in this study are:

I. Cropping system: stockless conventional farming (C) vs. organic farming (O)
II. Tillage: intensive tillage (IT) vs. no tillage (NT; for stockless conventional farming) or reduced tillage (RT; for organic farming)
III. Cover crop: non-legume (NL) vs. legume (L) vs. mixture (M) vs. control (C; fallow)

The cropping systems differed mainly in the type of fertilisation and the weed and pest control: In the stockless conventional systems (C), solely mineral fertilisers were used, weeds were controlled by synthetic herbicides, and insecticides or fungicides were applied when pest severity was above the incidence threshold. Generally, the fertilisation was done according to Swiss guidelines for fertilisation, which means that in the conventional systems, winter wheat and maize received 110 or 120 kg N/ha and 90 kg N/ha, respectively (see Table 1a). In the organic systems (O), fields were fertilised with cattle slurry at a target level of 1.4 livestock units ha^{-1} (on average 117 kg N_{total} ha^{-1} yr^{-1} or 51 kg $N_{mineral}$ ha^{-1} yr^{-1}). According to the Swiss organic rules, weed control was performed mechanically (hoeing, raking), and no pesticides were applied. The tillage regimes differed in the presence (IT) or absence (NT, RT) of conventional ploughing. As we wanted to represent the typical conservation tillage practice for each cropping system (stockless conventional vs. organic), reduced-tillage (RT) was performed in the organic system and no-tillage (NT) was performed in the stockless conventional system (Carr et al., 2012). Whereas in the reduced-tillage regime, soil tillage was performed to a target depth of 5 cm (with a disk or rotary harrow) primarily for weed control, no soil tillage at all occurred in the no-tillage regime and weed control was performed by additional use of the herbicide glyphosate. The combination of the two factors cropping system and tillage resulted in four investigated so-called production systems: C-IT (conventional intensive tillage), C-NT (conventional no tillage), O-IT (organic intensive tillage),