Europ. J. Agronomy 80 (2016) 45–54

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Estimating the environmental footprint of barley with improved nitrogen uptake efficiency—a Swedish scenario study

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ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form 9 June 2016
Accepted 20 June 2016

Keywords:
LCA
Life cycle analysis
Nitrogen use efficiency
Plant breeding
Simulation modelling
SOILNDB

ABSTRACT

Plant breeding is a powerful tool for improving nitrogen (N) uptake efficiency and thus reducing the environmental impact relating to crop production. This study evaluated the environmental impact of current barley production systems in two Swedish agricultural areas (South and East) compared with scenarios with improved N uptake efficiency at two levels, in which the fraction of mineral N available for daily crop uptake was increased by 50 and 100%. Life cycle assessment (LCA) methodology was used to quantify energy use, global warming potential (GWP) and acidification and eutrophication potentials along the production chain for spring barley with differing N uptake efficiency, but similar N application rate. The functional unit, to which all energy use and emissions were related, was 1 Mg barley grain. Energy use, GWP and acidification proved to be higher for the East production system, mainly due to lower yield, while eutrophication was higher for South. The two impacts most affected by improved N uptake efficiency were eutrophication and GWP, with GWP decreasing due to a combination of higher yield, soil carbon sequestration and lower indirect emissions of N_2O due to lower N leaching. Accounting for land savings due to increased yield, reducing the pressure to transform land elsewhere, would further lower the carbon footprint. Potential eutrophication per Mg grain was reduced by 15% in the production system with the highest N uptake efficiency in southern Sweden. Crops with improved N uptake efficiency can thus be an important complementary measure for reducing N losses to water, provided that the N application rate does not increase. However, incentives for farmers to maintain or even lower the N application rate might be required. Using simulation modelling is a promising approach for assessment of expected effects of improved crop varieties when no long-term experimental data are available. However, advanced crop models are required to better reflect the effect of plant breeding on e.g. expected yield. Future model development should involve expertise in plant breeding, plant physiology and dynamic crop and soil modelling.

1. Introduction

One major challenge for the 21st century is to produce enough food for a growing population while minimising the environmental impact of agriculture. So far, the increasing demand for food worldwide has largely been obtained by higher fertiliser input. The amount of nitrogen (N) mineral fertiliser applied increased seven-fold between 1960 and 1995, while global cereal production increased by only a factor of 2.4 (Tilman et al., 2002). Manufacturing of N mineral fertiliser through the Haber-Bosch process has continued to increase and almost 100 Tg N was produced in 2010 (Fowler et al., 2013). Increasing crop yield further by adding more N in intensive cropping systems is often considered inefficient due to diminishing returns (Tilman et al., 2002).

Manufacturing of N mineral fertiliser is currently associated with considerable use of non-renewable energy and emissions of greenhouse gases, despite improved energy efficiency at manufacturing sites and the introduction of abatement technologies for nitrous oxide at some plants (Brentrup and Pallière, 2008). Field application of N-containing fertilisers also gives rise to direct and indirect nitrous oxide (N_2O) emissions from soil, which strongly affects the carbon footprint from cereal production (Korsaeth et al.,

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http://dx.doi.org/10.1016/j.eja.2016.06.013
1161-0301/

Fig. 1. Map of Sweden showing the two cereal-producing areas considered in this study; South (parts of Skåne, marked in black) and East (Mälardalen & Hjälmardalen, marked in grey).

2014). Surplus N is also a significant cause of eutrophication of water ways. Agriculture is therefore a major target for different measures aimed at reducing the N load to the Baltic Sea (Stålnacke et al., 2014).

Soil organic carbon (SOC) sequestration can be an effective measure to mitigate global warming, and because soils contain more than twice the amount of carbon (C) in the atmosphere, even small changes in SOC are important. Annual C input to soil is the most important factor responsible for the build-up and sequestration of SOC, and any management technique that results in higher yields implies that more C is added through above- and below-ground (roots and rhizodeposits) crop residues (Bolinder et al., 2007). The SOC also promotes soil quality and can sustain or increase yields (Kätterer et al., 2012).

There are thus good environmental reasons for improving the N use efficiency and solutions are urgently needed to increase yield while maintaining or even decreasing the amount of N applied. Nitrogen use efficiency can be improved by various approaches, from modified and more precise N management to plant breeding. Plant breeding can be an effective tool for increasing N use efficiency, and thus sustainability, in crop production by introducing traits that generally allow maintained or increased crop yield at lower N fertiliser rates. Crop N use efficiency can be increased by modifying uptake, utilisation and remobilisation of plant-available N, so engineering of crops with increased N uptake efficiency currently appears a viable option (McAllister et al., 2012). Improved N uptake efficiency can be achieved by modifying the crop investments into nutrient uptake structures, e.g. producing crops with denser and deeper root systems (Skovby Rasmussen et al., 2015). An alternative is modification of nutrient uptake processes, e.g. in a transgenic approach stimulating over-expression of the enzyme alanine amino-transferase (AlaAT), resulting in increased yield under limited N availability (McAllister et al., 2012). To date, however, plants with modifications of this and other relevant enzymes have not produced consistent phenotypes expressing the improved characteristics in various genetic and environmental conditions (McAllister and Good, 2015), although results from field studies are promising (e.g. Good et al., 2007). Evaluation of the environmental impacts of these improved crop varieties is therefore a highly relevant issue.

A systems perspective is important when comparing cropping systems which differ from each other in terms of purchased inputs and their impact on the surrounding environment. Life cycle assessment (LCA) methodology has been extensively used for evaluation of agricultural production systems (Roy et al., 2009). LCA is a standardised methodology used for identifying opportunities for improved environmental performance and providing decision support for stakeholders in strategic planning and product development (ISO, 2006). In LCA, all stages in the production chain are considered, from production of purchased inputs to actual production and waste management, *i.e.* a cradle-to-grave perspective. Many LCA studies evaluate different management alternatives, but some have assessed the improvement potential of different crop traits and how LCA can be used as a decision-support tool in plant breeding. Niero et al. (2015) evaluated the effect of changed climate on the environmental performance of different barley cultivars in Denmark. McDewitt and Milà i Canals (2011) evaluated N use efficiency (in the broad sense of higher yield with lower N fertiliser input) and yield as plant breeding objectives for oats and found that LCA could be a complementary guiding tool for plant breeders to improve supply chain sustainability. Strange et al. (2008) compared a variety of rapeseed genetically modified for enhanced N