European Journal of Agronomy 101 (2018) 174–182

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Delayed and reduced nitrogen fertilization strategies decrease nitrogen losses while still achieving high yields and high grain quality in malting barley

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ARTICLE INFO

Keywords:
Nitrogen
Grain protein content
Grain retention fraction
Yield
Azodyn crop model
N use efficiency
Pareto-based ranking
Crop model

ABSTRACT

Nitrogen fertilizer applications are essential to achieve high yield and malting specifications in barley, but may also have a deleterious effect on the environment. Most strategies currently being implemented aim to optimize quantitative and qualitative production without taking environmental concerns into account. We used a barley crop model to pinpoint new nitrogen management plans maximizing the calibrated yields (yield of grains larger than 2.5 mm) and the grain quality whilst reducing N gaseous emission and N leaching. We compared the currently recommended N fertilization strategy in France and 44 new ones defined based on expertise knowledge, and differing in the amount of N applied, splitting patterns and time of application. The strategies providing the best compromise between the three criteria were identified by considering *Pareto* optimal solutions over 25 years in 35 French *départements* (equivalent to a county). We also identified *Pareto* optimal strategies for the seven years with the lowest yields and for years in which climatic conditions were unfavorable for efficient use of the early N supplies.

The current recommended N fertilization strategy resulted in a high proportion of situations satisfying malting grain protein content requirements, but also to high N losses. We pinpointed new N strategies resulting in better compromise between the three outputs studied. Some *Pareto* optimal strategies were particularly efficient to reduce N losses in all tested environments regardless of the climatic conditions. They, however, also slightly reduced calibrated yield compared to the reference strategy. Others interesting strategies performed better than the reference simultaneously for all three studied outputs, but depended on the region considered. A common feature of these strategies was later application of smaller doses of N. Our results, thus demonstrated that low-N strategies are possible for malting barley.

1. Introduction

French barley production is heavily dependent on the use of synthetic inputs, particularly nitrogen fertilizers. The average dose of nitrogen applied to barley (both winter and spring varieties) was 129 kg N ha^{-1} in 2011 (Agreste, 2013). Worldwide, more than half the N applied to crops is lost to the environment (Lassaletta et al., 2014; Raun and Johnson, 1999), due to low N use efficiencies. These losses are a threat to both human health and ecosystems (e.g. Erisman et al., 2013; Steffen et al., 2015). New N fertilization strategies are therefore required to reduce the impact of N-fertilizer use on the environment. These N fertilization strategies should also make it possible to achieve a high grain yield and adequate grain quality, to maintain the farmer's income despite the interannual variation of climatic conditions.

In malting barley, in addition to high yields, specific quality criteria must be met to optimize industrial processes (Fox et al., 2003). The price paid to farmers is much lower for grains not meeting these requirements, and in case of large gaps to requirements, the harvested volume can be downgraded to feed barley (Incograin, 2014). Barley grains are considered suitable for the French malting and brewing industry if they have a protein content between 9.5% and 11.5% (of dry weight), and if more than 90% of the harvested grains are larger than 2.5 mm. The direct maximization of the weight of grains > 2.5 mm large (herafter calibrated yield) may thus be of potential interest, as farmers receive premium prices. Thus, N fertilizer applications of malting barley crops must aim to strike a balance between yield, the

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https://doi.org/10.1016/j.eja.2018.09.001
Received 7 December 2017; Received in revised form 31 August 2018; Accepted 3 September 2018

proportion of grains of the desired size, the probability of grain protein content being in the malting range and N losses (N leaching and N gaseous emissions).

In Europe, N applications close to flowering on winter cereals generally increase yield (Delogu et al., 1998), but are not recommended for winter malting barley, to ensure that grain protein content do not become too high (Baethgen et al., 1995). Conversely, N fertilizer applications when crop growth restarts after winter generally result in high N gaseous loss to the environment. This is caused by low N use efficiency due to the low crop growth rate, as demonstrated for wheat (Limaux, 1999). Gaseous emissions after N application are indeed much smaller if crop N demand is high (Cassman et al., 2002; Crews and Peoples, 2004; Meynard et al., 2002*)*, which is not the case early in the crop cycle.

Weather conditions in the days following nitrogen application have also a strong impact on nitrogen use efficiency, crop growth, grain yield and grain quality (Tremblay and Bélec, 2006). High N losses occur if N is applied to soil that is not sufficiently moist (Campbell et al., 1995), or if no rainfall occurs shortly after N application (Addiscott and Powlson, 1992). This prevents the N to diffuse into the soil, and when applicable, the N pellets to dissolve. As predictions of weather conditions are uncertain, it is sometimes difficult to forecast the optimal dates and doses for nitrogen fertilizer applications. In the French barley belt (Fig S1.) high interannual and interregional climatic variability occurs, which may affect N use efficiency of synthetic fertilizer inputs and production (Beillouin et al., 2018a). When trying to identify locally the best N fertilization strategies for stable grain yield and quality, it is important to take this climatic variability into account. It is therefore highly challenging to determine the optimal management for N fertilizer applications for malting barley.

Providing they are used within their domain of validity, dynamic crop models are helpful tools to compare and rank numerous nitrogen fertilization strategies involving different splitting patterns and doses of nitrogen (Houlès et al., 2004; Jeuffroy et al., 2001; Ten Berge and Riethoven, 1997*)*. Such models have been widely used to identify N fertilization strategies reaching high yield (e.g. Kersebaum et al., 2005; Shaffer, 2002*)*, high protein content (e.g. Meynard et al., 2002) or low N leaching (e.g. Cannavo et al., 2008; Hyytiäinen et al., 2011; Wolf et al., 2005*)*. One of the principal advantages of such models is that they can be used to test much larger numbers of environment-by-management situations than could ever be assessed in multi-environment trial networks (Semenov and Halford, 2009). Models can also be used to estimate environmental outcomes that are difficult or costly to measure experimentally *(*Mary et al., 1999), such as N leaching and N gaseous losses. A dynamic crop model for malting barley has recently been developed and assessed (Azodyn-barley, Beillouin et al., 2018b). This model predicts yield, grain protein content, grain size and N losses to the environment in various conditions of N availability.

Based on the models outputs, various methods have been proposed for the simultaneous analysis of several criteria. Synthetic indicators taking several criteria into account, such as crop gross margin can be calculated (Antoniadou and Wallach, 2000; Makowski and Wallach, 2001). Makowski and Wallach (2001) and Houlès et al. (2004) considered impact on the environment by establishing a penalty function for gross margin based on soil mineral nitrogen content at harvest. Booltink et al. (2001) suggested that scenarios leading to a high probability of nitrogen loss to the environment should be removed from the scenarios analyzed, before the calculation of gross margin. In multi-objective optimization problems, interactions often occur between targets, and it is difficult or impossible to identify a single solution optimizing all objectives. The *Pareto*-based ranking approach is a powerful method for the combined evaluation of objectives without *a priori* weighting. This method also allows to identify all the strategies presenting interesting trade-offs between the various targets, so that the decision-maker can identify the best strategy according to his/her preferences. It is indeed possible to present the performance of all the tested strategies visually, which is known to facilitate decision-making (deVoil et al., 2006).

Thus, based on the results obtained for a dynamic barley crop model, this work aimed i) to rank N fertilization strategies according to the trade-offs between calibrated yield, the grain protein content and N losses, and ii) to determine whether the most favorable N fertilization strategies differ among environments within the main regions of the French barley belt.

2. Materials and methods

2.1. Range and characterization of the environments

The study included the 35 main French barley-producing *départements* (French geographic administrative units, equivalent to a county). We took climate variability into account, by analyzing climate data for a period of 25 years (from 1989–2013). Climate inputs (minimum and maximum temperature, incident radiation, rainfall and evapotranspiration) were obtained by the daily interpolation of weather data supplied by the Joint Research Center (European commission, DG, JRC, https://ec.europa.eu/jrc/en) over France, on a regular 25 km grid.

The mean agronomic and environmental performances of the N fertilization strategies were then calculated for each of the main regions of the French malting barley belt. French malting barley is produced in three main groups of *départements,* referred to hereafter as regions (Fig S1). Briefly, region 1 corresponds to the northern part of the malting belt, and is characterized by favorable growing conditions and high yields (mean of 109% the national yield over the 1989–2013 period). Regions 2 and 3 are located in the southern part of the malting belt and are characterized by more frequent stresses and lower mean yield (98% and 94% of the national yield in region 2 and 3 for the 1989–2013 period respectively). Each sub-region is characterized by different frequency of occurrence of climatic factors impacting barley yields (see Beillouin et al., 2018a for further details).

2.2. Set of N fertilization strategies considered

We considered 45 N fertilization strategies (Table 1) differing in the doses, dates and splitting of nitrogen fertilizer applications. We chose five doses of total N fertilizer applied, corresponding to 0.7, 0.8, 0.9, 1 and 1.1 times the mean total N dose (hereafter the reference dose) applied in each *département* for the years 1994, 2001 and 2006 (Agreste, 2013). Based on scientific and technical expertise, we defined

Table 1
Dose (kg N ha^{-1}) and splitting for the 45 N fertilization strategies. Splitting is coded with letters from A to E, depending on the number and target dates of N applications. The total dose of N applied (TOTAL) was calculated relative to the reference dose (mean N dose observed in each *département* for the years 1994, 2001 and 2006; Agreste, 1994, 2001, 2006) and a variation factor (X), taking values of 0.7, 0.8, 0.9, 1 and 1.1. BSE: beginning of stem elongation.

	Target date for N application:				
N splitting strategy	A (End-of-winter)	B (End-of-winter +10 days)	C (BSE)	D (BSE +15 days)	E (BSE +25 days)
AC	50		TOTAL-50		
AD	50			TOTAL-50	
BD		50		TOTAL-50	
BE		50			TOTAL-50
CE			50		TOTAL-50
ACD	50		TOTAL-90	40	
ACE	50		TOTAL-90		40
BCD		50	TOTAL-90	40	
BCE		50	TOTAL-90		40