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Yield gaps in Dutch arable farming systems: Analysis at crop and crop rotation level

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ABSTRACT

Arable farming systems in the Netherlands are characterized by crop rotations in which potato, sugar beet, spring onion, winter wheat and spring barley are the most important crops. The objectives of this study were to decompose crop yield gaps within such rotations into efficiency, resource and technology yield gaps and to explain those yield gaps based on observed cropping frequencies and alternative farmers' objectives. Data from specialized Dutch arable farms between 2008 and 2012 were used. Production frontiers and efficiency yield gaps were estimated using the stochastic frontier framework. The resource yield gap was quantified through the estimation of highest farmers' yields (Y_{HF}, average across farms with actual yields above the 90th percentile). Crop model simulations and variety trials were compiled to assess climatic potential yields (Yp) and technology yield gaps. The contribution of crop area shares and farmers' objectives to actual yields were assessed using regression analysis and based on five different farm level indicators (N production, energy production, gross margin, nitrogen-use efficiency and labour use), respectively.

The average yield gap per crop (as percentage of Yp which is given in parentheses) was: 29.2% (of 72.6 t ha^{-1}) for ware potato, 39.7% (of 71.6 t ha^{-1}) for starch potato, 26.4% (of 107.1 t ha^{-1}) for sugar beet, 32.3% (of 88.3 t ha^{-1}) for spring onion, 25.2% (of 12.3 t ha^{-1}) for winter wheat and 37.5% (of 10.4 t ha^{-1}) for spring barley. The efficiency yield gap ranged between 6.6% (starch potato) and 18.1% (spring onion) of Yp. The resource yield gap was lower than 10% of Yp for all the crops and the technology yield gap ranged between 7.1% (ware potato) and 30.7% of Yp (starch potato). There were statistically significant effects of potato (positive quadratic) and onion (positive) area shares on ware potato, sugar beet and winter wheat yields, of sugar beet area share (positive quadratic) on winter wheat yield and of cereal area share (negative) on sugar beet and winter wheat yields. Farmers' objectives explain part of the variability observed in crop yields which were 7–24%, 13–24% and 12–32% lower than Y_{HF}, respectively, for gross margin maximising, labour minimising and N use efficiency maximising farms. In addition, there was a significant positive relationship between gross margin and the yield of ware potato, sugar beet and winter wheat. By contrast, no significant relationships were found between crop yields and NUE or labour use.

We conclude that most of the yield gap is explained by the efficiency yield gap for ware potato and spring onion and by both the efficiency and technology yield gaps for sugar beet and cereals. The resource yield gap explains most of the yield gap of seed potato, and the technology yield gap of starch potato. The results regarding the effects of cropping frequency and crop rotations to crop yields are not very conclusive which suggest that agronomic principles become less evident at 'systems level' given the number of interacting factors at crop rotation level. Finally, although N and energy production are lower for gross margin maximising farms, most crop yields are not significantly different between farms with the highest N and energy production compared to farms performing best on economic (gross margin) objectives.

1. Introduction

Crop yield gaps can be estimated and explained at different spatial scales using a wide range of methodologies (Beza et al., 2017; van Ittersum et al., 2013). For instance, yield gap analysis at field (crop) level is usually performed using field trials and/or farm surveys in combination with crop growth simulation models (e.g. Affholder et al., 2012; Subedi and Ma, 2009; Abeledo et al., 2008) and with multivariate statistics (e.g. Delmotte et al., 2011; Fermont et al., 2009; Tittonell et al., 2008). Such type of analyses provide good insights about the

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limiting factors to crop growth but they fail to capture the multi-dimensional aspects of crop production occurring at farm and farming systems level.

Understanding the scope for sustainable intensification of current farming systems requires an in-depth, and integrated, assessment of crop yield gaps at the farm level for three main reasons. First, farmers make decisions about which activities to pursue and how to allocate the available resources given their personal objectives and circumstances (Kanellopoulos et al., 2014; Mandryk et al., 2014). Second, there can be incompatibilities or synergies between different activities performed within the same farm (Hochman et al., 2014; Dogliotti et al., 2003; Struik and Bonciarelli, 1997). Third, the farm integrates both biophysical and socio-economic components of agricultural systems. Therefore, farm level analysis using individual farm data are important to expose interactions between different activities as well as the potential limitations and consequences of different management and livelihood strategies (Reidsma et al., 2015b; Kanellopoulos et al., 2012; Tittonell et al., 2009).

Arable farming systems in the Netherlands provide a good case study to test a suite of methodologies aiming at explaining yield gaps at both crop and farm level. Dutch arable farms are organized into crop rotations in which a succession of different crops is repeated every certain number of years. The most important crops are ware, seed and starch potato, sugar beet, spring onion, winter wheat and spring barley. In 2015, approximately 155,000 ha (21% of the total arable area) of potato were harvested in the Netherlands, followed by 130,000 ha of winter wheat, 70,000 ha of sugar beet, 35,000 ha of spring barley and 20,000 ha of spring onion (CBS, 2015). In addition, farms operate close to the climatic potential yield (Yp, http://www.yieldgap.org) and resource use efficiencies are strongly influenced by economic performance (Mandryk et al., 2014), environmental legislation limiting fertiliser and pesticide use (Boatman et al., 1999) or market regulations (e.g. sugar beet quota).

The objectives of this study are twofold: 1) to disentangle crop yield gaps within Dutch arable farming systems using a standard methodological approach and 2) to explain those yield gaps based on observed cropping frequencies and alternative farmers' objectives. For this purpose, we applied the theoretical framework developed by Silva et al. (2017) to analyse yield gaps for the most important crops cultivated in arable farming systems in the Netherlands. We hypothesized that yield gaps of the main crops (ware potato, sugar beet and winter wheat) are relatively small (80% of Yp) and that much of this yield gap can be explained by farm and crop rotation factors rather than field and crop level conditions.

2. Theoretical framework

A generic arable farm system with a four-year crop rotation composed of potato (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L.) and spring barley (*Hordeum vulgare* L.) is depicted in Fig. 1. This rotation is a typical example of how rotations looked like in The Netherlands traditionally but they have become more diversified. In addition, there are also distinct regional differences with more (lighter soils) or less (heavy soils) root and tuber crops depending on the soil type. Following Ewert et al. (2011), in this system it is important to differentiate processes and flows occurring at crop rotation level from the ones occurring at crop level as these two levels are nested and have different spatial (i.e. farm area vs crop area) and temporal scales (i.e. length of crop rotation vs crop growing season). The concepts developed to disentangle and explain yield gaps at crop and crop rotation level in this study are described in this section.

In this paper, the term yield refers to the land productivity of an individual crop and is expressed in ton fresh matter (FM) ha^{-1} whereas the term production refers to the total production at farm level calculated as the sum of the different crop yields in kg N ha^{-1} or MJ ha^{-1}. Non-substitutable (i.e. water and nutrients) and substitutable inputs (e.g. herbicides and nematicides) for crop growth are referred to as inputs and those can be aggregated at crop or crop rotation level.

2.1. Disentangling yield gaps at crop level

Yield gap analysis is useful to understand the relative contribution of growth-defining, -limiting and -reducing factors to actual yields. For this purpose, Silva et al. (2017) introduced a framework integrating concepts of production ecology (van Ittersum and Rabbinge, 1997) and methods of frontier analysis (Farrell, 1957) which can be used to explain crop yield gaps when applied to individual crop and/or farm data. As a result, crop yield gaps (i.e. difference between Yp and actual yields, Ya) were decomposed into an efficiency, resource and technology yield gap (Fig. 1A).

Five different yield levels are required to decompose yield gaps at crop level. Actual yields (Ya) are the yields currently achieved by farmers and can be compiled through for example farm surveys. Technical efficient yields (Y_{TEx}) refer to the maximum yield which can be achieved with current input use and can be estimated using methods of frontier analysis (Farrell, 1957). Allocative efficient yields (Y_{AE}) can be defined as the Y_{TEx} which optimise levels of crop production given farmers' objectives and resource constraints (similar to P_{AE} in Fig. 1B). Highest farmers' yields (Y_{HF}) provide an indication of the maximum yields currently achieved by farmers and can be estimated as the mean of Ya above the 90th percentile. Finally, the climatic potential yield (Yp) is the maximum theoretical yield which a genotype can achieve in a well-defined biophysical environment (van Ittersum and Rabbinge, 1997).

The efficiency yield gap is defined as the difference between Y_{TEx} and Ya and expresses by how much yield can be increased with current levels of inputs in a particular environment. Yield differences between farms using similar inputs can then be explained by differences in timing, spacing and form of the inputs applied, observed variation in sowing dates as well as rotational effects due to interactions between crops (see below), while controlling for differences in biophysical conditions. The resource yield gap can be estimated as the difference between Y_{HF} and Y_{TEx} and it indicates the additional yield which can be obtained in case input use is increased to the level used to achieve Y_{HF}. Finally, the technology yield gap refers to the difference between Yp (or Yw in rainfed conditions) and Y_{HF} and can be explained by existing limiting factors to production (i.e. von Liebig's law of the minimum) and/or the lack of precision agriculture practices and new varieties able to exploit Yp. Rotational effects may also explain the technology yield gap in case the farms included in the sample share a similar crop rotation plan and hence show little variation in this factor.

2.2. Explaining yield gaps at crop rotation level

Understanding crop yield gaps requires looking beyond the field scale and individual season. Below, we frame the importance of rotational effects over time and alternative farmers' objectives when allocating resources to multiple activities within the theoretical framework proposed in Fig. 1.

2.2.1. Rotational effects on crop yields

A crop rotation can be defined as an ordered succession of crops which are cultivated repetitively every certain number of years (cf. Wijnands et al., 2002). Crop rotations are particularly important to preserve soil fertility and to control pests, diseases and weeds. However, their 'efficacy' depends on a number of factors including the species of crops cultivated, their frequency and sequence, the length of the complete cycle and the number of different crops, among others. Further information about the importance of these factors for the productive, economic and environmental performance of Dutch arable crop rotations can be found in Dogliotti et al. (2003) and Vereijken (1997).