

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 (Y_p) 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 Y_p 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 Y_p . The resource yield gap was lower than 10% of Y_p for all the crops and the technology yield gap ranged between 7.1% (ware potato) and 30.7% of Y_p (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; Titttonell 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; Titttonell 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 (Y_p , <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 Y_p) 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 Y_p and actual yields, Y_a) 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 (Y_a) are the yields currently achieved by farmers and can be compiled through for example farm surveys. Technical efficient yields ($Y_{\text{TE}}^{\text{ex}}$) 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 $Y_{\text{TE}}^{\text{ex}}$ 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 Y_a above the 90th percentile. Finally, the climatic potential yield (Y_p) 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 $Y_{\text{TE}}^{\text{ex}}$ and Y_a 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 $Y_{\text{TE}}^{\text{ex}}$ 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 Y_p (or Y_w 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 Y_p . 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).

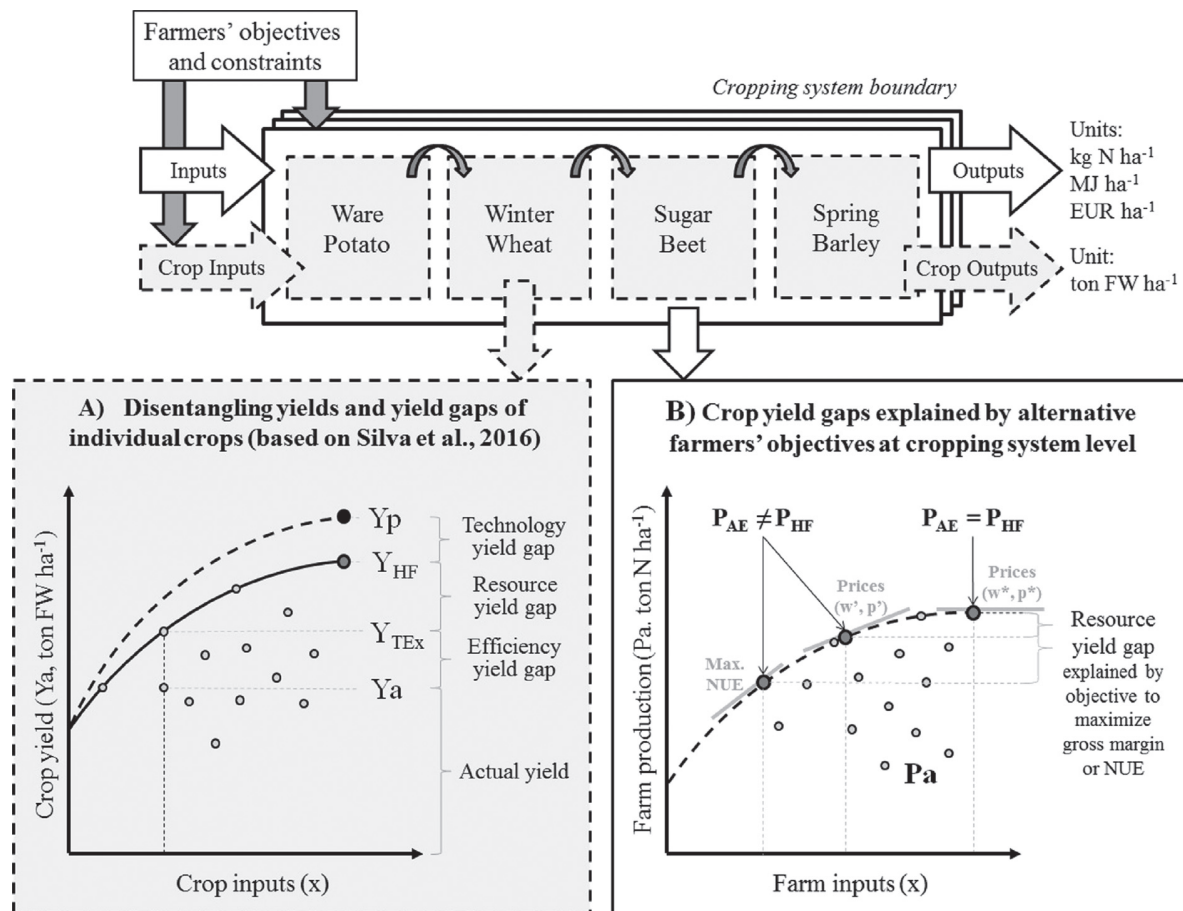


Fig. 1. Representation of an arable crop rotation and theoretical framework to A) disentangle crop yield gaps and B) explain those considering alternative farmers' objectives. Y_p is the climatic potential yield as defined by van Ittersum and Rabbinge (1997). Y_{HF} , Y_{TE} and Y_a are abbreviations for highest farmers' yield, technical efficient yield at a specific input level and actual yield of a specific crop across multiple farms, respectively. P_{HF} , P_{AE} and P_a stand for highest farmers', allocative efficient and actual production at crop rotation level. Solid grey lines in B) represent the maximum nitrogen use efficiency (NUE) and gross margin for two input-output price ratios, (w', p') and (w^*, p^*) . Single input-output relationships are shown for illustration purposes only. See text for further explanation.

The aforementioned rotational effects need to be taken into account when trying to understand yield variability and yield gaps from a crop rotation perspective. In general, it can be argued that rotational effects explain part of the efficiency, resource and technology yield gap (Fig. 1A). Different farms sharing similar crop management practices and biophysical environment may still exhibit different efficiency yield gaps in case they cultivate a different number of crop species or cultivate the same crop species in different frequencies and sequences (Mazzilli et al., 2016; Rijk et al., 2013). Crop rotations may also affect the resource yield gap as follows: including legumes as previous crop reduces the need for N application (Reckling et al., 2016; Plaza-Bonilla et al., 2017) and increasing crop diversity helps reducing the pressure of biotic factors and the use of pesticides (Andert et al., 2016; Landis et al., 2008; Struik and Bonciarelli, 1997). Both strategies can explain why different farms require different input levels to achieve similar yield levels. Finally, rotational effects can also explain the technology yield gap in case all farms in the sample use sub-optimal crop rotations. It is important to note that individual effects are generally hard to isolate because they are dynamic and can be confounded with other factors (e.g. renting extra land allows to grow the same specialised crop on this extra land if the rented land is different from year to year).

2.2.2. Farmers' objectives and constraints

Farmers' objectives and resource constraints determine the intensity with which inputs are used and hence, the production level of different activities. We define the difference between maximum production at

crop rotation level (P_{HF} , kg N ha⁻¹) and the production observed under different farmers' objectives (e.g. maximum gross margin, P_{AEcon} in kg N ha⁻¹) as 'production trade-off'. This is expected to occur, as generally farmers prioritize economic (or environmental) performance over production maximisation (Monjardino et al., 2015; Mandryk et al., 2014). Production trade-offs have socio-economic causes and may arise if different objectives have different optimal production levels.

Production trade-offs can be quantified using individual farm data as the difference in farm production between production and, for instance, gross margin maximising farmers (Fig. 1B). Maximum production cannot be based on yield levels, as yields of different crops cannot be directly compared. Instead, N or energy production can be used as proxies. The top 10th percentile farmers of N or energy production and gross margin can then be compared. Other important objectives which can be assessed following the same rationale are minimum labour use ($P_{AElabour}$) or maximum nitrogen use efficiency (NUE) at crop rotation level as an indicator for environmental performance (P_{AEenv}).

3. Material and methods

3.1. Farm accountancy data

Individual farm data from specialized arable farms in the Netherlands between 2008–2012 were used in this study (see Supplementary Material). Such data are collected every year by the Wageningen Economic Research with the purpose of monitoring the

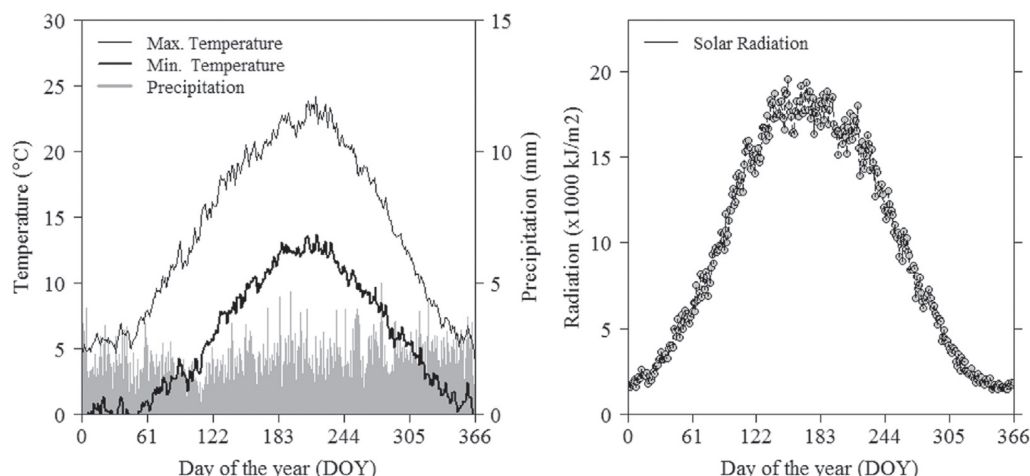


Fig. 2. Mean daily maximum and minimum temperature (°C), rainfall (mm) and solar radiation (kJ m⁻²) for the period 1970–2012 in De Bilt, The Netherlands. Source: Royal Netherlands Meteorological Institute (KNMI).

income and economic performance of agricultural holdings in the Netherlands (van der Veen et al., 2014). The farms monitored are selected from the most recent agricultural census based on a disproportional stratified random sample, i.e. a random sample of farms selected from the agricultural census is assigned to a specific strata defined by the type of farming (e.g. arable farms) and the economic size class ($\geq 25,000$ €).

The Netherlands is a relatively homogeneous country with a temperate maritime climate. The variation in temperature and radiation as well as the distribution of rainfall is well captured by the meteorological station located in De Bilt (Fig. 2). Annual precipitation is on average 810 mm yr⁻¹ (1970–2012) and it falls uniformly throughout the year. Minimum temperatures are around 0°C during the winter months (December–February) and have a maximum of about 12.3°C in July/August. Maximum temperatures follow a similar temporal pattern with a minimum value of 5.4°C during the winter and a maximum of about 22.3°C during the summer. Solar radiation increases during the first half of the year to a value of about 17.8 MJ m⁻² in the summer after which it steadily declines during the second half of the year. In terms of edaphic conditions, three main soil types can be identified in the country: marine clay soils in the north and south-western areas, sandy soils in most of the south- and central-eastern areas and, somehow less representative, peat soils in the north and center-western areas.

Arable crops are mostly cultivated between March and October with the exception of winter wheat which is cultivated between November and August. Most farms grow a succession of root and tuber crops and cereals over multiple years, in particular sugar beet, potato and winter wheat. Spring onion and spring barley are also important crops but they are cultivated by a smaller number of farmers. Generally, potato is the crop with largest gross margin but it is important to differentiate between three crop rotations: 1) starch potato are cultivated once every two years and in relatively marginal soils with the objective of maximising starch production, 2) seed potato are cultivated for high quality medium size tubers which depend on initial seed quality, crop management and haulm killing date, and 3) ware potato are mostly cultivated for the french fries industry with specific quality and size restrictions. Descriptive statistics of the crop level data used are provided in Table A1 (see Supplementary Material). The sample size, i.e. total number of farms in the dataset, between 2008–2012 was ca. 175 farms per year. We assumed one crop rotation per farm as the data does not allow for a more detailed analysis, but this may not fully represent actual farmers' practice.

3.2. Yield gap analysis at crop level

3.2.1. Efficiency yield gap

Stochastic frontier analysis (Kumbhakar and Lovell, 2000; Aigner et al., 1977; Meeusen and van den Broeck, 1977) was employed to estimate crop-specific efficiency yield gaps. The translog functional form was chosen for this analysis because it explicitly considers the first- and second-order terms, including interactions, across inputs and outputs and it does not pose restrictive assumptions about the shape of the production frontier. Its mathematical formulation as well as the estimation of the efficiency yield gap and $Y_{\text{TE}x}$ are specified as follows:

$$\ln y_{it} = \alpha_0 + \sum_k \beta_k \ln x_{kit} + \frac{1}{2} \sum_k \sum_j \theta_{kj} \ln x_{kit} \times \ln x_{jit} + \sum_t \delta_t DT_t + v_{it} - u_{it} \quad (1)$$

$$\text{Eff}Y_{G_{it}} = 1 - \exp(-u_{it}) \quad (2)$$

$$Y_{\text{TE}x_{it}} = Y_{a_{it}} \times \exp(-u_{it})^{-1} \quad (3)$$

where y_{it} is the yield of a specific crop in farm i and period t , x_{it} a vector of input k and j defined according to principles of production ecology (van Ittersum and Rabbinge, 1997) and DT_t a year dummy. The random error term v_{it} is assumed to be $N(0, \sigma_v^2)$, and independent of the u_{it} , which accounts for technical inefficiency in production and is assumed to be independently distributed following $N(\mu, \sigma_u^2)$. The parameters to be estimated are α_0 (intercept), β_k (first-order terms), θ_{kj} (second-order terms) and δ_t (year effects). $Y_{\text{TE}x}$ and the efficiency yield gap are based on u_{it} and defined as in Section 2.1. All parameters and error terms were estimated with maximum likelihood using the R package 'frontier' (Coelli and Henningsen, 2013).

Quantitative input-output data for a set of unique combinations of farm $\times$ crop $\times$ year were used to estimate the stochastic frontier models (Eq. 1) and the efficiency yield gap (Eq. 2). Fresh matter yield (y, kg FM ha⁻¹) of potato (ware, seed and starch), sugar beet, spring onion, winter wheat and spring barley were defined as dependent variables. Independent variables (x) were selected to capture the role of growth-defining, -limiting and -reducing factors to actual yields.

Growth-defining factors were included in the model as a year-dummy in order to control for year-specific climatic conditions referring to e.g. temperature and solar radiation. No regional dummies were included because the Netherlands is considered a homogeneous climatic region (van Wart et al., 2013). We did not control for different varieties,

planting/sowing dates and densities and previous crop, as data were not available, so these factors are captured in the efficiency yield gap. The variables considered as growth-limiting factors were N and P use (expressed in kg ha⁻¹) and soil type expressed as a dummy variable with four levels namely, clay (clay content > 80% of the farm area), sand (sand content > 80%), loess (loess content > 80%) and mixed (clay, sand and loess content < 80%). The N use variable corresponds to plant available N applied, i.e. the N applied with mineral fertilisers together with the N fertiliser replacement value of organic amendments (which can be understood as the equivalent effect of organic amendments expressed in mineral fertiliser-N). Fungicide, herbicide, insecticide and nematocidal variables (expressed in kg a.i. ha⁻¹) were used to control for growth-reducing factors in the crop production systems to which they are relevant. Finally, a dummy variable was included to differentiate between conventional (*n* = 169) and organic (*n* = 16) production systems to control for potential differences in nutrient, pest, disease and weed management. The *y* and *x* variables included in the production frontier were mean-scaled and log-transformed prior to the analysis.

3.2.2. Resource yield gap

The resource yield gap indicates the potential to increase yields due to increases in input use and it can be quantified as the difference between *Y_{HF}*, i.e. the mean across observations of *Y_a* above the 90th percentile, and *Y_{TE}* estimated using stochastic frontier analysis. We did not differentiate between soil types due to non-statistically significance of yield differences between soil types for most crops (see Table 1). In order to explain the resource yield gap, we further grouped the observations into lowest yielding farms (*Y_{LF}*, i.e. mean across observations of *Y_a* below the 10th percentile) and average yielding farms (*Y_{AF}*, i.e. mean across observations with *Y_a* between the 10th and 90th percentiles) and compared the application of plant available N across the three groups. Furthermore, the statistical significance of the parameters β_k and θ_k in Eq. 1 provide an indication of the most important input(s) explaining the resource yield gap. Results are presented for 2012 only because no major differences in the resource yield gap were observed during the period analysed (2008–2012).

3.2.3. Technology yield gap

Climatic potential yields (*Y_p*) set the biophysical boundaries of yield gap analysis and therefore it is important to assess the difference between *Y_p* and *Y_{HF}*. We opted to use estimates of *Y_p* instead of water-limited yields (*Y_w*) due to the high uncertainty of the latter estimates related to the depth of water table and frequent occurrence of capillary rise. However, we cannot rule out water stress because irrigation is not a default in the Netherlands. Furthermore, we assumed there is no spatial variability in *Y_p* for the arable crops cultivated in the Netherlands (<http://www.yieldgap.org>) since the climate is so homogeneous across the country. Estimates of *Y_p* for ware potato, winter wheat and spring barley were simulated with WOFOST (Boogaard et al., 2013) for an average sowing date and during the period 1992–2008 (see Reidsma et al., 2015b). Further details about model calibration and validation can be found in Wolf et al. (2011). In case of starch potato, sugar beet and spring onion, *Y_p* was obtained from variety trials (Rijk et al., 2013). No yield benchmark was used for seed potato due to the peculiarities of the seed potato production system (see Section 3.1). Further details about the *Y_p* estimates considered are provided in Table A2 (see Supplementary Material).

Standard moisture contents were used to convert *Y_p* from dry to fresh matter to ensure these estimates are comparable with the *Y_a* values observed in the accountancy database. The standard dry matter contents considered per crop were the following: 21.5% for ware potato and for seed potato, 20.0% for sugar beet and spring onion and 84.0% winter wheat and spring barley. In case of sugar beet and starch potato, we further assumed a standard sugar content of 17% (Suiker Unie, personal communication) and an underwater weight of 524 g (Avebe, personal communication), respectively.

3.3. Resource and crop allocation at farm level

3.3.1. Influence of cropping frequency

'Cropping frequency' is the only rotational effect we could analyse using the available data as we had no information about 'cropping sequence'. Cropping frequency was computed as the ratio between the area (in ha) of an individual crop and the total cultivated land (in ha). We had no means to exclude the area of crops cultivated on rented land as that information was not available for each individual crop and the succession of crops grown on rented land was unknown. This is particularly relevant in the case of potato cultivation as it is common practice in the Netherlands that farmers rent extra land to grow this crop (Fig. A2, Supplementary Material). Therefore, we did the analysis for potato using the subset of farms with less than 33.3% of rented land and less than 40.0% of potato in the total area. We considered these thresholds to restrict the analysis to farms with a relatively low share of rented land (because higher potato area shares of potato point at the importance of potato cultivated on rented land, where rotations are likely wider) and to account for the legal norm of potato cultivation in the Netherlands.

The relationship between crop yields in year *t* and crop area share in year *t* – 1 was studied using regression analysis. We allowed for linear and quadratic effects in order to test whether the increasing share of one crop leads to an increase (or decrease) of crop yields or if a maximum (or minimum) yield level occurs for a particular crop at a specific crop area share. We focused our analysis on the proportion of potato (ware, seed and starch potato), sugar beet, spring onion and cereals (winter wheat and spring barley), see Fig. A3 in Supplementary Material for an overview, and assessed the contribution of each of them to the yield of ware potato, sugar beet and winter wheat. Regressions were fitted to the entire sample of farms available (except for potato, see above) pooling data from four different time periods: 2008–2009, 2009–2010, 2010–2011 and 2011–2012. The *lm* function of R (R Development Core Team, 2008) was used for the analysis.

3.3.2. Trade-offs between farmers' objectives

The impacts of farmers' objectives on crop yield gaps were assessed for clay soils and the period 2008–2012 (*n* = 97 farms) in order to average environmental conditions and rotational effects across years. The crops at stake in this analysis were ware and seed potato, sugar beet, spring onion, winter wheat and, spring barley as there were no observations of starch potato in clay soils. Actual farm production, *P_a*, was calculated in N (kg N ha⁻¹) and energy terms (MJ ha⁻¹) for farm *j* and crop *i* as follows:

$$PaN_j = \frac{\sum_i Yield_{ij} \text{ (kg FM ha}^{-1}\text{)} \times N \text{ content}_i \text{ (}\%\text{)} \times Area_{ij} \text{ (ha)}}{\sum_i Area_{ij} \text{ (ha)}} \quad (4)$$

$$PaEnergy_j = \frac{\sum_i Yield_{ij} \text{ (kg FM ha}^{-1}\text{)} \times Energy \text{ content}_i \text{ (MJ kg FM}^{-1}\text{)} \times Area_{ij} \text{ (ha)}}{\sum_i Area_{ij} \text{ (ha)}} \quad (5)$$

N concentration and energy content in the crop products were compiled from de Haan and van Geel (2013)¹ and Meul et al. (2007)², respectively. Maximum farm production, *P_{AEprod}*, was quantified as the mean *P_a* in terms of N and energy across the farms above the 90th percentile for each of these indicators.

Gross margin was quantified from the farm accountancy data as the difference between economic returns from crop activities and material

¹ 3.3 kg N t⁻¹ FM of ware potato tubers, 3.0 kg N t⁻¹ FM of seed potato tubers, 1.8 kg N t⁻¹ FM of sugar beet, 2.2 kg N t⁻¹ FM of onion bulbs, 16.8 kg N t⁻¹ FM of wheat grains and 12.6 kg N t⁻¹ FM of barley grains.

² 3.4 MJ kg FM⁻¹ for potato tubers, 5.3 MJ kg FM⁻¹ for sugar beet roots, 1.3 MJ kg FM⁻¹ for onion bulbs, 15.5 MJ kg FM⁻¹ for winter wheat grains and 15.8 MJ kg FM⁻¹ for spring barley grains.

Table 1

Parameter estimates of the crop-specific stochastic frontier models estimated for Dutch arable farming (2008–2012). The default soil type is ‘clay’, except for starch potato which is ‘mixed’. Significance codes: ‘***’ 0.1% ‘**’ 1% ‘*’ 5%.

Variables	Ware potato	Seed potato	Starch potato	Sugar beet	Spring onion	Winter wheat	Spring barley
<i>Production frontier</i>							
Intercept	0.335***	0.228***	0.118***	0.046	0.288***	0.184***	0.204***
Nitrogen	−0.045	0.001	0.231	−0.003	0.061	0.016	0.043
Nitrogen ²	−0.008	−0.003	−1.119**	−0.003	0.007	−0.002	0.005
Phosphorus	0.003	−0.015	0.058	−0.009	0.012	0.001	−0.030**
Phosphorus ²	−0.014	−0.005	−0.336**	−0.001	0.001	−0.001	−0.002
Fungicide	0.058**	−0.024	0.089	0.005	−0.128*	0.024*	0.021
Fungicide ²	0.006*	0.003	−0.122	0.001	−0.006	0.002	0.001
Herbicide	0.046	0.060	0.074	−0.023	0.060	0.004	−0.018
Herbicide ²	−0.004	−0.002	−0.002	−0.004	−0.019	−0.001	0.000
Insecticide	0.011	−0.006	−0.001	−0.003	0.041***		
Insecticide ²	−0.001	−0.003	0.000	0.000	0.007*		
Nematicide	0.003	0.002	0.012				
Nematicide ²	−0.001	−0.001	0.002				
Certification_Organic	−0.389***	−0.172*	−0.132**	0.031	−1.753	−0.026	0.057
Year_2009	−0.002	0.074**	−0.002	0.094***	0.019	0.038*	0.124***
Year_2010	−0.085*	0.071*	−0.038	0.032	−0.024	0.023	0.013
Year_2011	−0.004	0.009	0.023	0.082***	0.025	−0.112***	0.018
Year_2012	−0.034	0.084	0.065*	0.061*	−0.008	−0.073***	0.078*
Soil type_Sand	−0.042	−0.416***	0.032	−0.039			−0.112***
Soil type_Mixed		−0.540***		−0.044		−0.123***	−0.053
Soil type_Loess				0.065			
Nitrogen × Phosphorus	0.007	0.006	0.103	0.002	0.000	0.007	0.001
Nitrogen × Fungicide	−0.006**	−0.016	0.466***	0.000	0.000	0.005	−0.001
Nitrogen × Herbicide	0.006*	0.013**	−0.045	−0.021	−0.001	−0.002	−0.001
Nitrogen × Insecticide	−0.002	−0.004	−0.027	0.002	0.001		
Nitrogen × Nematicide	0.001	−0.003	0.001				
Phosphorus × Fungicide	0.002	0.029**	−0.202**	0.000	0.000	0.001	0.001
Phosphorus × Herbicide	0.004	−0.029***	−0.067	−0.003	0.000	0.001	−0.002
Phosphorus × Insecticide	0.004*	0.002	0.034**	−0.001	0.001		
Phosphorus × Nematicide	0.002	−0.002	0.048***				
Fungicide × Herbicide	0.000	0.000	0.066*	−0.011***	0.026	−0.002	−0.001
Fungicide × Insecticide	0.001	0.001	0.000	0.000	−0.013		
Fungicide × Nematicide	0.003	0.001	0.017**				
Herbicide × Insecticide	0.002	0.004	−0.005	0.002	−0.001		
Herbicide × Nematicide	0.003	0.001	0.008*				
Insecticide × Nematicide	0.000	0.000	0.001				
Year × Nitrogen	0.016***	0.002	−0.037	0.006	−0.007	0.004	0.001
Year × Phosphorus	0.004	0.000	−0.005	0.000	0.001	−0.001	0.004
Year × Fungicide	0.000	0.025***	−0.029*	0.000	0.024**	−0.003	−0.001
Year × Herbicide	−0.006*	−0.017*	0.001	−0.008	−0.016	−0.002	0.005
Year × Insecticide	0.000	0.005	0.002	0.000	−0.006*		
Year × Nematicide	−0.001	0.000	0.003				
Soil type_Sand × Nitrogen	0.089	−0.046	−0.220	−0.033			−0.047
Soil type_Sand × Phosphorus	0.004	0.025	−0.002	−0.002			−0.001
Soil type_Sand × Fungicide	0.027	0.016	0.040	0.000			−0.004
Soil type_Sand × Herbicide	0.013	0.001	−0.044	0.037			0.030
Soil type_Sand × Insecticide	−0.005	−0.006	0.006	0.007			
Soil type_Sand × Nematicide	0.003	−0.007	−0.003				
Soil type_Mixed × Nitrogen		−0.018		−0.114		−0.371***	0.021
Soil type_Mixed × Phosphorus		−0.005		0.004		0.040	0.077**
Soil type_Mixed × Fungicide		−0.290***		0.010		−0.006	−0.023
Soil type_Mixed × Herbicide		0.160*		0.002		0.025	−0.003
Soil type_Mixed × Insecticide		−0.028		0.007			
Soil type_Mixed × Nematicide		0.008					
Soil type_Loess × Nitrogen				−0.080			
Soil type_Loess × Phosphorus				0.003			
Soil type_Loess × Fungicide				0.000			
Soil type_Loess × Herbicide				−0.002			
Soil type_Loess × Insecticide				0.028			
<i>Model evaluation</i>							
$\sigma^2 = \sigma_v^2 + \sigma_u^2$	0.104***	0.043***	0.018***	0.031***	0.113***	0.036***	0.079***
$\gamma = \sigma_u^2 / \sigma^2$	0.959***	0.602***	1.000***	0.752***	0.969***	0.936***	0.947***
TE scores (%)	79.8	88.4	90.5	89.0	78.8	87.1	81.6
Sample size (n)	406	461	134	756	286	506	336

‘TE scores’ refer to the average of the field-specific Technical Efficiency scores (i.e. 100 minus the efficiency yield gap expressed in %) obtained for each stochastic frontier model.

costs (i.e. seeds, fertilisers, pesticides, energy and other). Input and output prices were deflated to 2005 prices using the consumer price index available from CBS (2015). Maximum gross margin was calculated as the mean gross margin of the farms above the 90th percentile of

this indicator, and P_{AEcon} (in N or energy per ha) was calculated for the same group of farms. A similar approach was followed to identify the maximum NUE at crop rotation level (kg N kg^{−1} N) which was estimated for farm j based on crop i as follows:

Table 2

Descriptive statistics of Ya and Yg, decomposed into the efficiency, resource and technology yield gaps (t ha⁻¹ and % of Yp) for arable crops in the Netherlands during the period 2008–2012. Standard deviations are presented between brackets. n.a. = not applicable.

	Actual yield (Ya)		Efficiency Yg		Resource Yg		Technology Yg	
	t ha ⁻¹	%	t ha ⁻¹	%	t ha ⁻¹	%	t ha ⁻¹	%
Ware potato	51.3 (± 11.3)	70.6	12.7 (± 8.0)	17.5	3.4 (± 7.8)	4.6	5.2 (± 1.5)	7.1
Seed potato	34.5 (± 8.2)	n.a.	4.3 (± 1.5)	n.a.	8.3 (± 8.0)	n.a.	n.a. (± n.a.)	n.a.
Starch potato	43.3 (± 4.2)	60.5	4.7 (± 3.9)	6.6	1.7 (± 3.7)	2.4	22.0 (± 1.9)	30.7
Sugar beet	78.9 (± 10.8)	73.7	9.4 (± 4.4)	8.8	9.3 (± 7.8)	8.7	9.5 (± 3.8)	8.9
Spring onion	60.0 (± 13.1)	68.0	16.0 (± 10.6)	18.1	3.8 (± 8.0)	4.3	8.7 (± 2.9)	9.9
Winter wheat	9.1 (± 1.2)	74.0	1.3 (± 0.9)	10.6	0.3 (± 0.7)	2.4	1.5 (± 0.5)	12.2
Spring barley	6.6 (± 1.3)	63.5	1.5 (± 0.9)	14.4	0.6 (± 0.9)	5.8	1.8 (± 0.4)	17.3

^a Data of the resource yield gap refer to the multiple-input stochastic frontier model (Table 1).

$$N \text{ output}_j \text{ (kg N)} = \sum_i \text{Yield}_{ij} \text{ (kg FM ha}^{-1}\text{)} \times N \text{ content}_i \text{ (\%)} \\ \times \text{Area}_{ij} \text{ (ha)} \quad (6)$$

$$N \text{ applied}_j \text{ (kg N)} = \sum_i (\text{Fertiliser.N}_{ij} + \text{Manure.N}_{ij}) \text{ (kg N ha}^{-1}\text{)} \\ \times \text{Area}_{ij} \text{ (ha)} \quad (7)$$

$$N \text{ input}_j \text{ (kg N)} = N \text{ applied}_j \text{ (kg N)} + N \text{ indigenous}_j \text{ (kg N)} \quad (8)$$

$$NUE_j \text{ (kg N kg}^{-1} \text{ N)} = \frac{N \text{ output}_j \text{ (kg N)}}{N \text{ input}_j \text{ (kg N)}} \quad (9)$$

P_{AEnv} was calculated based on the farms above the 90th percentile for NUE. The amount of N applied per farm (Eq. 7) includes the amount of mineral N applied with fertilisers and the amount of mineral and organic N applied with organic manures; hence, higher NUE can be expected among farmers using only mineral fertilisers as compared to farmers using both mineral and organic N sources (Schroder, 2014). The variable 'N indigenous' in Eq. 8 includes N inputs from seed, atmospheric deposition and biological N fixation and these were retrieved directly from the dataset. Finally, the minimum labour use (hr ha⁻¹) was calculated as the mean labour use of the farms below the 10th percentile of this indicator, and $P_{AElabour}$ was based on this group of farms. The Mann-Whitney *U* test was used to check for significant differences between the level of each indicator across different farmers' objectives and between crop yields achieved by production maximising farms (N or energy) and by farms with a different objective (gross margin, labour use or NUE). This non-parametric test was used because for most indicators the hypothesis that the sample comes from a population which has a normal distribution was rejected (results of the Shapiro-Wilk test not shown).

4. Results

4.1. Yields and yield gaps at crop level

The parameter estimates characterizing the crop-specific production frontiers are provided in Table 1. The gamma values indicate that the inclusion of two random errors is appropriate for all crops, except for seed potato ($\gamma = 0.602$), because most of the unexplained variability in crop yields can be attributed to the efficiency yield gap (u_{ij}) rather than to statistical noise (v_{ij}). Results for starch potato should be interpreted with caution as the statistical tests may be biased when $\gamma = 1$. A detailed interpretation of the coefficients presented in Table 1 is provided for each crop in Appendix.

The importance of environmental conditions for yield variability were analysed in terms of year and soil type effects (Table 1). Statistically significant year effects during the period 2008–2012 are observed for all crops except spring onion. Crop yields in clay soils are significantly higher than in mixed and/or sandy soils only for seed potato and cereals and no statistically significant yield differences

across different soil types are observed for the other crops. As for certification type, actual yields of ware, seed and starch potato are significantly lower in organic than in conventional production systems while no such difference is observed for the other crops.

Variability in crop yields is mostly associated with the management of growth-reducing rather than growth-limiting factors (Table 1). There is a significant relationship (first and second-order terms) between fungicide use and ware potato yields and between insecticide use and spring onion yields. Moreover, there is a significant linear relationship between fungicide use and spring onion yield (negative) and winter wheat yield (positive). The use efficiency of fungicides is positively associated with herbicide and nematicide use for starch potato and negatively associated with herbicide use for sugar beet. For starch potato, the efficiency in the use of herbicides is positively associated with nematicide use. For seed potato, yield responses to fungicide are lower in mixed than in clay soils while yield responses to herbicide are greater in mixed than in clay soils. Finally, the use efficiency of fungicides increased over time for seed potato and spring onion but declined for starch potato. A decline in the efficiency of herbicide use is observed for ware and seed potato and in insecticide use for spring onion.

Management of growth-limiting factors affects the use efficiency of inputs associated with the control of growth-reducing factors, particularly for potato production systems. For example, greater responses to herbicides are observed with greater amounts of plant available N applied for ware and seed potato. Plant available N applied also affects the use efficiency of fungicides, negatively for ware potato and positively for starch potato. Other examples include increasing N use efficiency over time for ware potato, negative quadratic relationship between yield and nutrients (N and P) for starch potato, negative linear relationship between yield and P and greater yield response to P in mixed than clay soils for spring barley, and lower yield response to N in mixed than in clay soils for winter wheat.

The magnitude of yield gaps in Dutch arable farming is about 30% of Yp for all crops, except starch potato and spring barley for which the gap is ca. 40% (Table 2, which provides data in absolute terms as well). This yield gap is mostly explained by the efficiency yield gap (around 20% of Yp) for crops such as ware potato and spring onion while its contribution is much lower (around 10%) for starch potato, sugar beet and cereals. The resource yield gap is small for all crops ranging between 2% of Yp for winter wheat and starch potato to 9% for sugar beet. Finally, the technology yield gap is as high as 31% for starch potato, 12–17% for cereals and slightly lower (less than 10%) for ware potato, sugar beet and spring onion.

The magnitude and variability of the efficiency yield gap is presented in Fig. 3 (2008–2012) and that of the resource (using N as an example) and technology yield gaps in Fig. 4 (2012 data is shown for illustration purposes). A large variability in the efficiency yield gap is observed for ware potato, spring onion, winter wheat and spring barley (Fig. 3A, E, F and G, respectively): for these crops efficiency yield gaps as large as 50% are still observed for a number of farms and at different Ya levels. Data presented in Fig. 4 for 2012 corroborate these results.

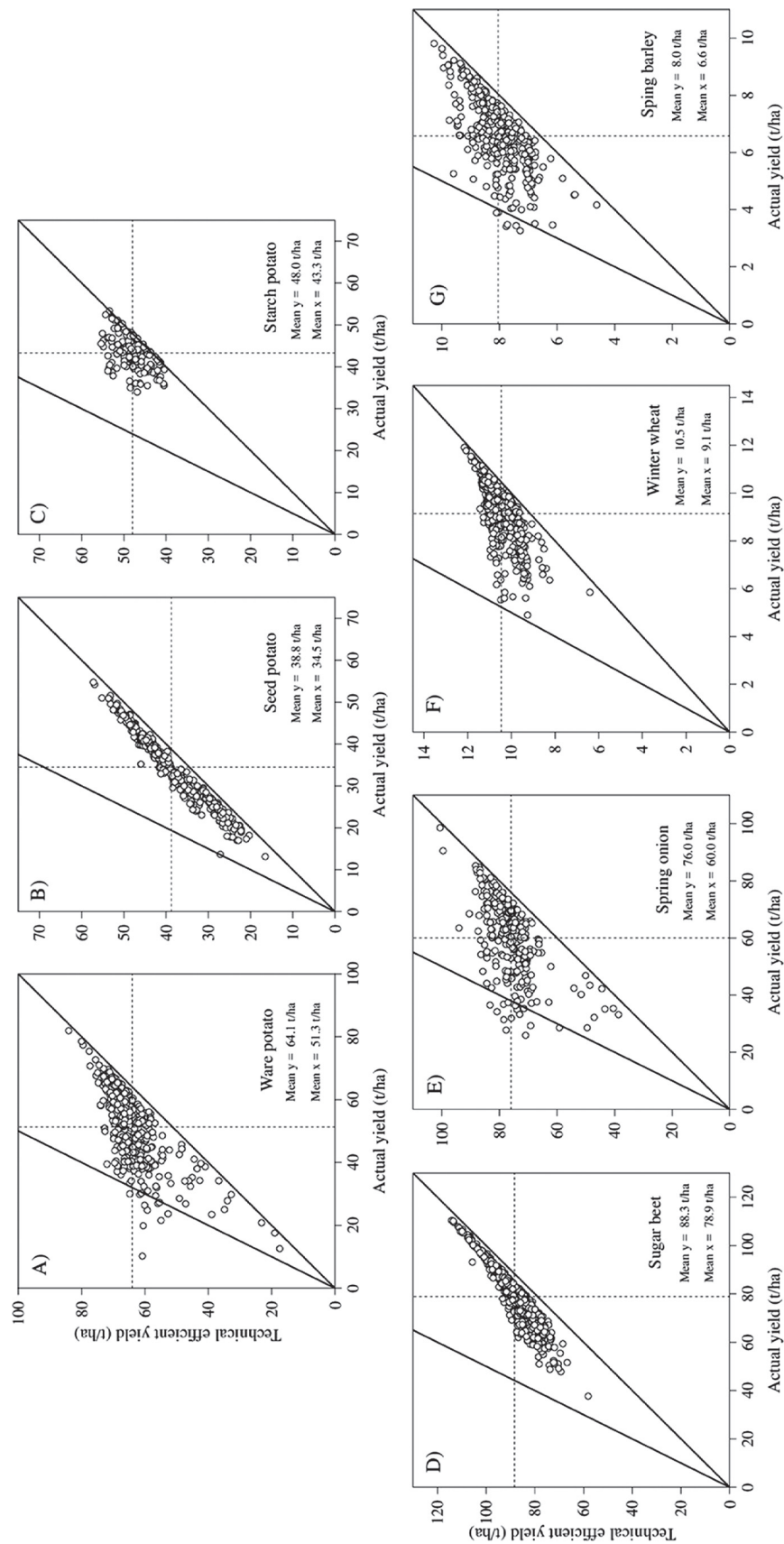


Fig. 3. Efficiency yield gaps of A) ware potato, B) seed potato, C) starch potato, D) sugar beet, E) spring onion, F) winter wheat and G) spring barley in arable farming systems in the Netherlands. Data refers to the period 2008–2012; solid lines represent the 1:1 and 1:2 lines while the dashed lines represent the mean Y_a (x-axis) and Y_{TEF} (y-axis).

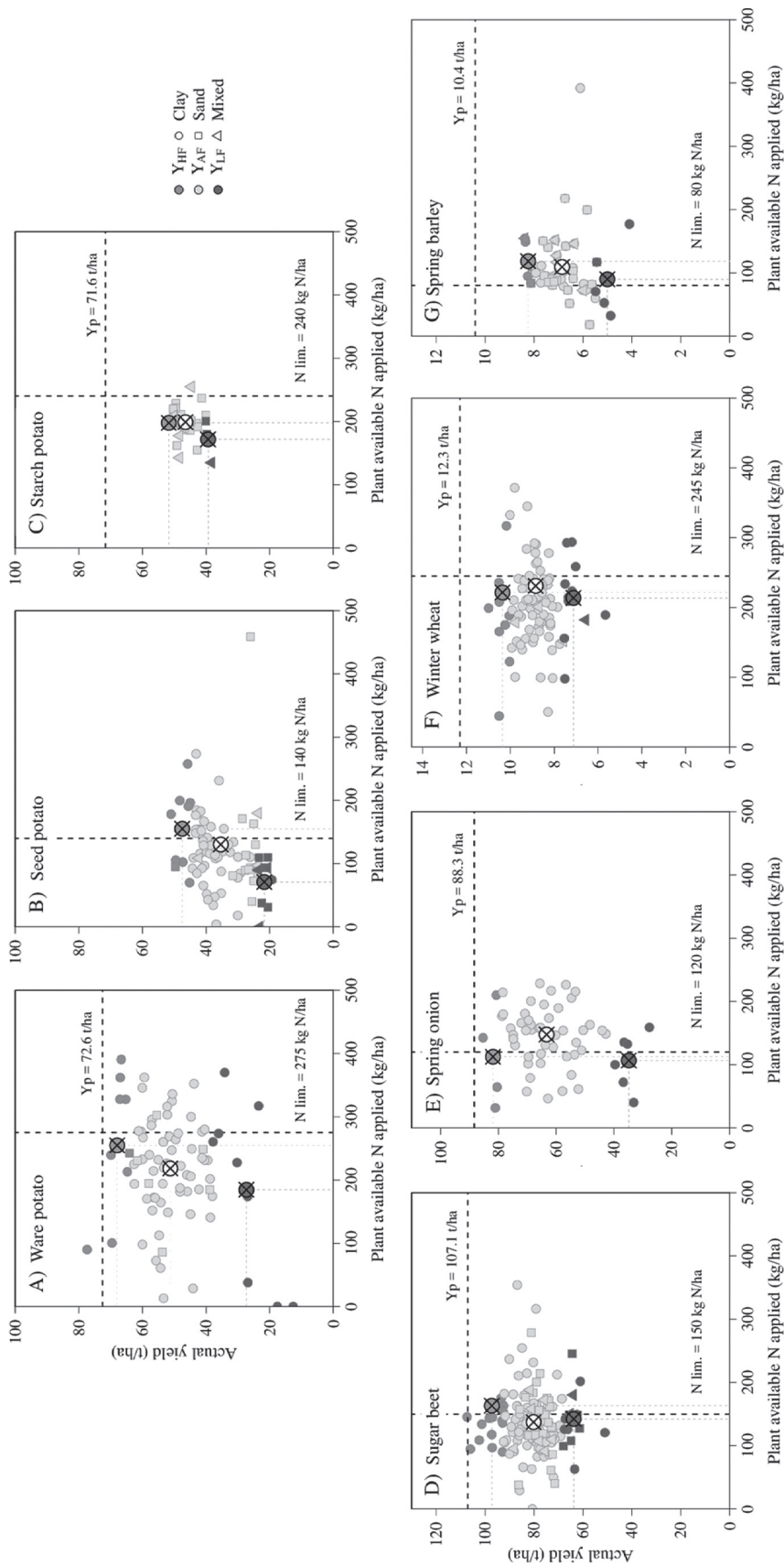


Fig. 4. Resource (of N) and technology yield gaps of A) ware potato, B) seed potato, C) starch potato, D) sugar beet, E) spring onion, F) winter wheat and G) spring barley in arable farming systems in the Netherlands. Plant available N applied refers to the N supplied with mineral fertilisers and the N fertiliser replacement value of organic amendments. Each dot refers to a single farm in the year 2012 and soil types are differentiated into clay, sand and mixed. Horizontal dashed lines present the crop-specific Y_p estimates while vertical dashed lines present the N application standards on clay soils for the year 2012 (LNV, 2009). Y_{HF} = highest farmers' yield; Y_{AF} = average farmers' yield and Y_{LF} = lowest farmers' yield.

The resource (N) yield gap is relatively small for all crops because Y_{HF} , Y_{AF} and Y_{LF} are obtained with similar applications of plant available N, which comply with the N application standards at crop level for most farms except for spring onion and spring barley (Fig. 4). However, yield responses to plant available N applied are still evident for ware and seed potato (Fig. 4A and B). Finally, the technology yield gap is larger for starch potato and cereals than for the other crops (see difference between Y_p and Y_{HF} in Fig. 4).

4.2. Insights at crop rotation level

Based on our framework, the efficiency yield gap must be explained by the timing, placing and form of the inputs applied and by rotational effects between different crops. Due to lack of data, we cannot assess empirically the contribution of the first set of factors to the efficiency yield gap but we do not expect crop management to be optimal due to biophysical and socio-economic constraints (see further discussion in Section 5.1). Alternatively, we focused our analysis on the relationship between cropping frequencies and crop yields, and explored the contribution of different farmers' objectives for crop yield gaps and farm performance.

4.2.1. Cropping frequency and yield variability

The distribution of the proportion of the farm area allocated to potato is slightly right-skewed because few farms cultivate a large share of their land with ware, seed or starch potato (Fig. 5A–C). However, most of the farms have a share of potato area lower than 40% which corresponds to the cultivation of one potato crop every 2.5 years. It is important to mention that there is a significant positive linear relationship between the proportion of potato and the proportion of rented land in the farm (Fig. A2 and Table A3, see Appendix) meaning that effects of potato areas on crop yields are confounded with the effects of rented land. Nonetheless, and despite the low R^2 estimated (less than 20%), statistically significant (quadratic) relationships are found between the proportion of potato and the yield of ware potato, sugar beet and winter wheat. Maximum yield levels are observed at ca. 30% of potato share for ware potato and winter wheat and 25% for sugar beet.

The share of sugar beet per farm follows a normal distribution, with most farms cultivating 10–15 % of their farm area with this crop (Fig. 5D–F). No statistically significant relationships are found between the share of sugar beet and the yield of ware potato and sugar beet while a significant quadratic effect is observed with the yield of winter wheat, though with very low R^2 (about 2%).

Similarly to the proportion of potato, the share of spring onion in total farm size follows a distribution which is right-skewed (Fig. 5G–I). The majority of farms cultivate spring onion on 5–10 % of their total area and only very few farms have an area share of spring onion greater than 20%. There is a statistically significant relationship between crop yield and area share of spring onion, i.e. the yields of ware potato, sugar beet and winter wheat increase linearly with an increasing proportion of spring onion in the farm plan. However, the fitted regressions have a R^2 lower than 13%.

There is a large variation in the proportion of cereals (i.e. winter wheat and spring barley) cultivated across farms, with very few farms not cultivating cereals and other farms very specialized in cereal production (Fig. 5J–L). Overall, the proportion of cereals follows a distribution which is right-skewed due to few specialized cereal farms. There is a significant negative relationship between the proportion of cereals and sugar beet and winter wheat yield, but again, the R^2 is very low (3%).

4.2.2. Farmers' objectives and yield variability

The maximum farm production is 166 kg N ha⁻¹ (Fig. 6A) to which ware potato, sugar beet and winter wheat contribute ca. 82% (Fig. 6B). This level of production is observed for the group of farms with highest N and energy production whereas gross margin and NUE maximisation

as well as labour minimisation result in lower farm N production: about 20% less for maximum gross margin and NUE and 35% less for minimum labour use (Fig. 6A). In terms of NUE, the maximum value observed is ca. 0.90 kg N kg⁻¹ N (Fig. 6B). Farms with maximum N production, energy production and gross margin have NUE values of ca. 0.65–0.69 kg N kg⁻¹ N while NUE is ca. 0.55 kg N kg⁻¹ N in farms with minimum labour use.

There is a large variation in gross margin between different farmers' objectives (Fig. 6D). The maximum value of gross margin observed is 5056 € ha⁻¹ for gross margin maximising farms. Compared to gross margin maximising farms, production maximising farms obtain 37% (N production) or 30% (energy production) lower gross margin while labour minimising farms obtain 66% lower and NUE maximising farms 23% lower gross margin. Moreover, only gross margin maximising farms reach the maximum gross margin observed (see error bars). Spring onion, ware potato and seed potato contribute to about 74% of the maximum gross margin, with seed potato contributing to nearly 50% (Fig. 6E). The average labour use observed for labour minimising farms is 21.5 hr ha⁻¹ (Fig. 6F). Farms maximising production, economic or NUE objectives use on average much more labour (23 to 47 hr ha⁻¹) than labour minimising farms.

There are few statistically significant yield differences for most crops between farms maximising N production and farms maximising energy production and gross margin (Fig. 6G–L) which indicates that differences in N production across these objectives are mostly due to differences in crop area shares (Fig. 6B and E). As compared to N production maximising farms, significantly lower yields are observed in case of ware potato, sugar beet, spring onion and spring barley for labour minimising farms and lower ware potato and sugar beet yields for NUE maximising farms. In general, labour minimising and NUE maximising farms tend to have lower yields for all crops compared to production, energy or gross margin maximising farms. Some farms with maximum N production achieve Y_{HF} for ware potato, sugar beet and winter wheat. In contrast, gross margin maximising farms achieve yields reaching Y_{HF} for seed potato and spring onion. Yields of seed potato, sugar beet and winter wheat close to Y_{HF} are achieved by farms with maximum NUE and Y_{HF} is not achieved by labour minimising farms for any crop.

The relationship between different indicators and yields of ware potato, sugar beet and winter wheat is provided in Fig. 7. There is a significantly positive relationship between N production and gross margin (Fig. 7A), whereas no significant relationship is found between N production on the one hand and NUE and labour use on the other hand (Fig. 7B and C). Despite the large variability and low R^2 of the fitted linear regressions (maximum of 22% in Fig. 7A), there is a positive and statistically significant relation between gross margin and the yield of ware potato, sugar beet and winter wheat (Fig. 7D). No significant relationship is found neither between NUE and crop yield (Fig. 7E) nor between labour use and crop yield (Fig. 7F).

5. Discussion

5.1. Crop yield gaps in Dutch arable farming

Crop yield gaps in Dutch arable farming systems ranged between 25% (winter wheat) and 40% (starch potato) of Y_p (Table 2). For ware potato and spring onion, the yield gap was mostly explained by the efficiency yield gap while the resource yield gap was particularly important for seed potato, and the technology yield gap for starch potato. The efficiency and the technology yield gaps are equally important for cereals (winter wheat and spring barley) and, the yield gap of sugar beet is equally explained by the three intermediate yield gaps. The small resource and technology yield gaps estimated for most crops indicate that farmers are applying input levels high enough to achieve Y_p , but the high application of plant available N (sometimes above the N application standard particularly for spring onion and spring barley) is

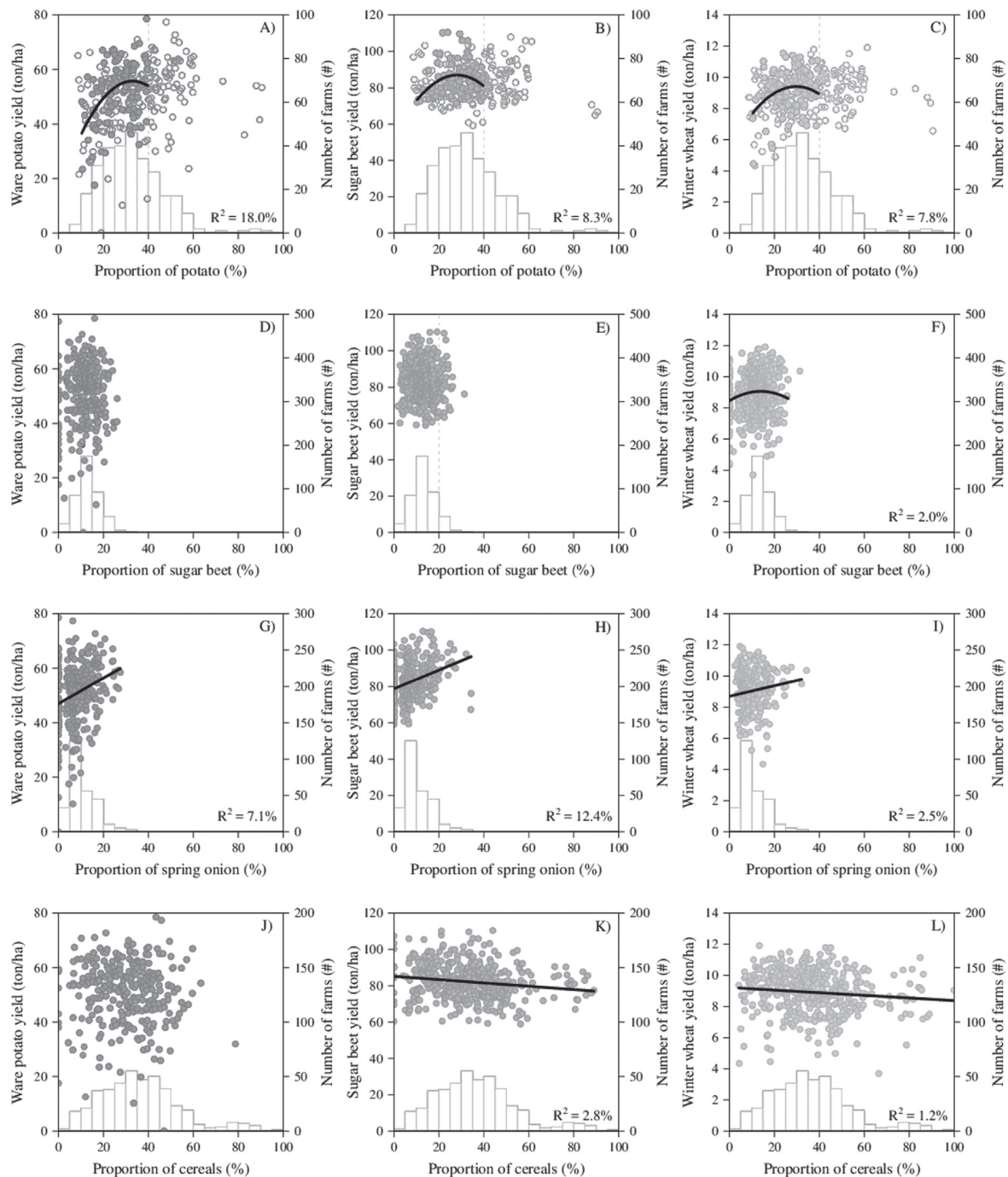


Fig. 5. Relationship between Ya of ware potato, sugar beet and winter wheat in year t and the proportion of potato, sugar beet, spring onion and cereals in year $t - 1$. Each dot represents an individual farm with area share and crop yield observed in the following periods: 2008–2009, 2009–2010, 2010–2011 and 2011–2012. Light grey dots in A), B) and C) were not included in the regression analysis due to the high proportion of rented land (more than 33.3%). The histogram represents the distribution of the share of specific crop(s). Statistically significant linear and/or quadratic regressions are presented as solid lines (parameter estimates and significance levels are provided in Tables A4, A5 and A6, see Supplementary Material).

likely to induce losses and environmental impacts.

The efficiency yield gap can be explained by sub-optimal crop management in terms of timing, placing and form of inputs (not tested empirically due to lack of data, Fig. 4) and/or to a minor extent by sub-optimal cropping frequencies from a production perspective (Fig. 5). The timing of operational activities may be suboptimal because of delayed harvest of the previous crop (Mazzilli et al., 2016), poor soil trafficability in key periods (Droogers et al., 1996), unfavourable weather conditions (van Oort et al., 2012) and, labour and machinery

constraints on large farms (Reidsma et al., 2015a). Narrow crop rotations may also explain the relatively large efficiency yield gap as they exacerbate negative effects of biotic factors to crop yields (Scholte and s'Jacob, 1990). The strategic decision of increasing the share of tuber and root crops in the crop rotation, at the expense of cereals, is likely to be explained by farmers' objectives of maximising economic performance instead of crop production (Fig. 6B and E). However, this might not always be possible due to production quotas in place as it is the case for sugar beet in the European Union (Fig. 5D–F). Compliance with a

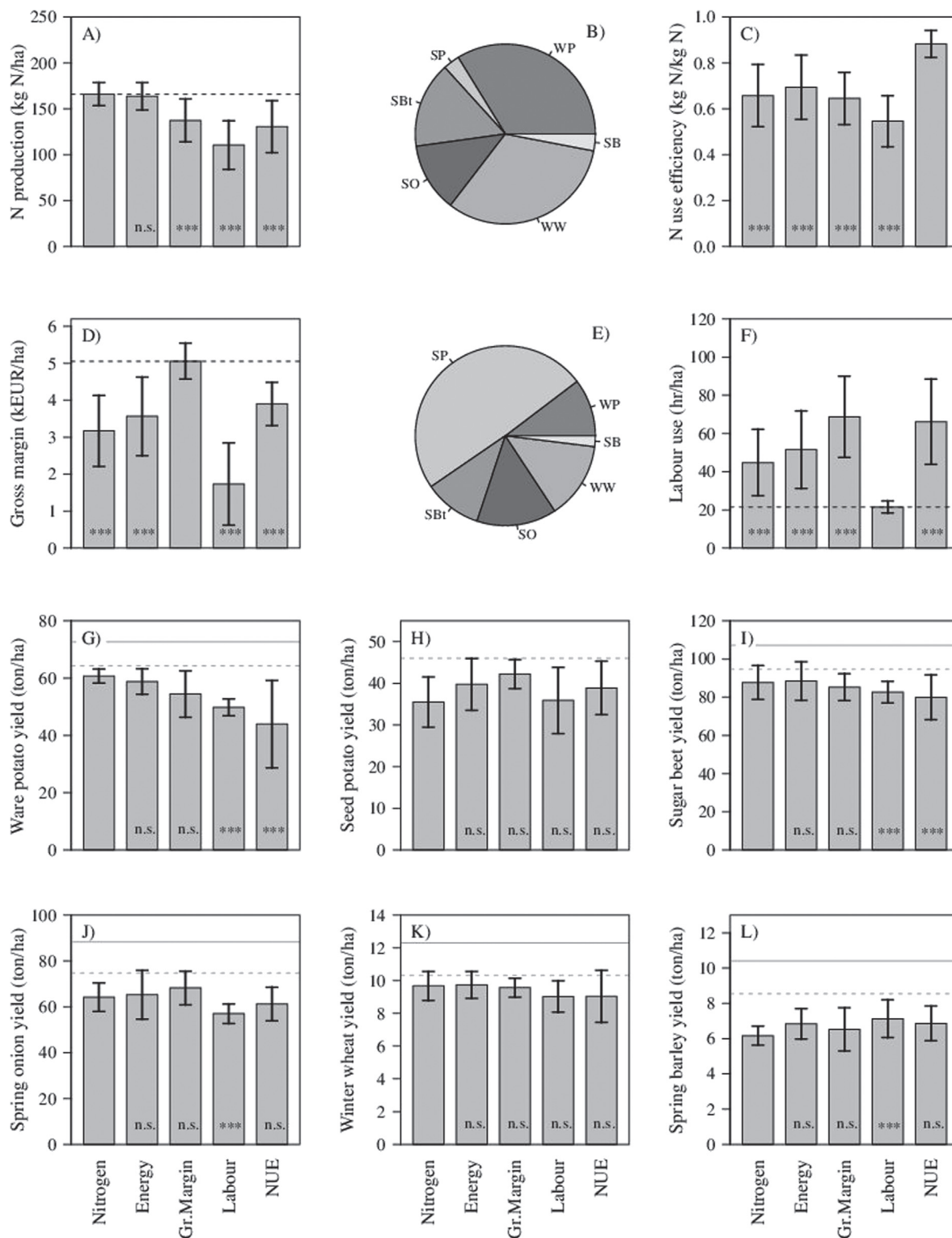


Fig. 6. Production trade-offs for Dutch arable farms in clay soils during the period 2008–2012. The top four barplots show the performance of the farmers' objectives maximising N and energy production, maximising gross margin, minimising labour use and maximising NUE at crop rotation level in terms of A) N production, C) NUE, D) gross margin and F) labour use, respectively; dashed lines show the mean observed across the farms above the 90th percentile of each indicator, except for NUE which has a benchmark of 1 kg N kg⁻¹ N. The six barplots presented below show differences in Ya across different objectives for the following crops: G) ware potato, H) seed potato, I) sugar beet, J) spring onion, K) winter wheat and L) spring barley, respectively; in these figures the dashed and solid lines represent the crop-specific Y_{HF} and Y_p , respectively. Error bars are standard deviations of the mean. Crop area shares underlying the maximum N production and maximum gross margin are presented in the pie charts B) and E), respectively (codes: WP = ware potato; SP = seed potato; SBt = sugar beet; SO = spring onion; WW = winter wheat; SB = spring barley). The underlying data are presented in Table A7 (see Supplementary Material). Significance codes: 'n.s.' = not significant; '***' = significant at 5%.

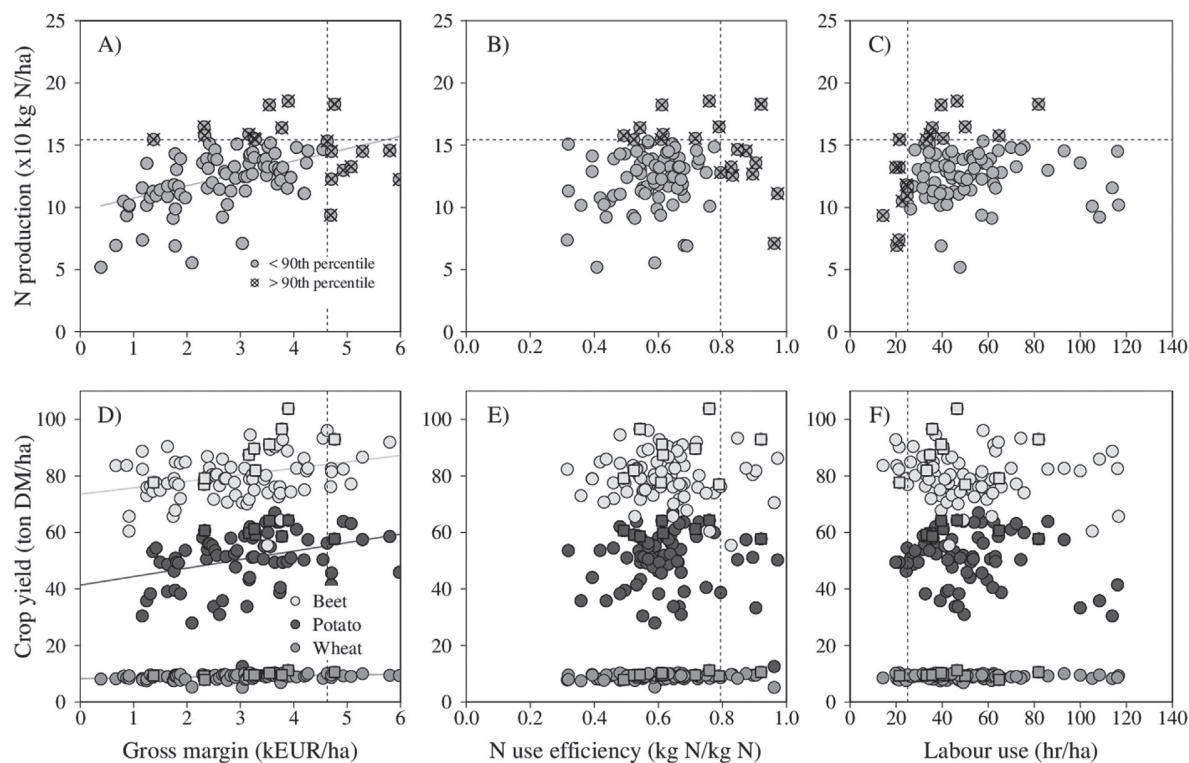


Fig. 7. Relationship between N production at farm level (kg N ha^{-1}) and A) gross margin in k€ha^{-1} , B) NUE in $\text{kg N kg}^{-1} \text{N}$ and C) labour use in hr ha^{-1} ; and between yield of ware potato, sugar beet and winter wheat (t FM ha^{-1}) and D) gross margin, E) NUE and F) labour use. Dashed lines represent the 90th percentile value of each indicator while full lines are fitted, and statistically significant, linear regressions. Crossed symbols in A), B) and C) highlight the observations above the 90th percentile for the indicators presented in the x-axis and/or the y-axis. Square symbols in D), E) and F) identify the farms above the 90th percentile of N production. Parameter estimates and significance levels are provided in Tables A8 - A11 (see Supplementary Material).

particular mode of production may introduce further constraints to reduce the efficiency yield gap. We found lower crop yields in organic than in conventional production systems, similarly to [de Ponti et al. \(2012\)](#) and [Seufert et al. \(2012\)](#), but statistically significant differences were observed only for ware, seed and starch potato (Table 1). Nonetheless, these results must be interpreted cautiously because of the small sample size available for organic farms.

The technology yield gap is partly explained by water-limitations ($Y_p - Y_w$) during the growing season, particularly for starch potato and cereals, as irrigation is not default in the Netherlands, and certainly not for cereals. Despite the relatively humid climate and the presence of capillary rise in many areas, it is likely that water stress plays a role in some parts of the growing season, in particular on sandy and mixed soils where most of the starch potato is cultivated. In fact, higher yields were observed in clay than in sandy and mixed soil types for seed potato, winter wheat and spring barley which may be explained by less water stress in clay soils (Table 1). In fact, this points at Y_p not being the correct benchmark for yield gaps. Differently from the other crops, rotational effects explain the technology rather than the efficiency yield gap of starch potato because most farmers cultivate this crop in a narrow crop rotation which increases the pressure from cyst nematodes. No other technologies seem to explain the technology yield gap because most farmers use up-to-date and high-yielding technologies (e.g. varieties; [Rijk et al., 2013](#)).

Beneficial effects of cropping frequencies on crop yields are difficult to show in our study (Fig. 5), which challenges statements about the effectiveness of crop diversity and crop rotations for crop productivity ([Ponisio et al., 2014](#)). This discrepancy may be partly due to data problems because we were not able to take into account factors such as cropping sequence nor to disentangle confounding effects of rented land due to lack of data. In addition, the high input levels used by farmers (Fig. 4) may mask negative effects of narrow crop rotations which lead

to weaker and more inefficient root systems in terms of water and nutrient uptake. However, we would expect to capture any beneficial effects associated with crop rotations with our methodology if such effects would be outstanding.

[Lobell et al. \(2009\)](#) and [van Ittersum et al. \(2013\)](#) suggested that the exploitable yield for farmers is ca. 80% of Y_p (or Y_w), since the remaining 20% of the yield gap will not be closed because of economic and environmental considerations and management constraints of the farmer. Our analysis partly supports the aforementioned statement because the difference between crop yield across the different farmers' objectives and crop-specific Y_p ranged between 20 and 40% (Fig. 6G-L). Ware potato, sugar beet, spring onion and winter wheat yields were on average 20 to 25% lower than Y_p while yields of spring barley were on average 35% lower than Y_p for gross margin and NUE maximising farms and labour minimising farms (Fig. 6G-L). However, most crop yields are not significantly different between farms with the highest production compared to farms performing best in economic (gross margin) objectives. Also Fig. 7D suggests little trade-off between crop yields and gross margin. Differences in N production across farmers' objectives (Fig. 6A) are mainly due to differences in crop area shares (e.g. Fig. 6B and E) which indicates that maximisation of N (or energy) production at crop rotation level requires a particular cropping pattern rather than closing yield gaps at crop level.

5.2. Methodological considerations

The methodology applied builds largely on the framework and methods used by [Silva et al. \(2017\)](#). The most obvious improvement to the current analysis would be to estimate the inefficiency effects model ([Battese and Coelli, 1995](#)) in order to explain quantitatively the efficiency yield gap for each crop (e.g. [Mazzilli et al., 2016](#)). This was not done in this paper for two reasons: 1) the dataset lacked detailed field

level data referring to time, form and space of inputs as well as preceding crop and field history and 2) for most crops there were not enough degrees of freedom to analyse the influence of individual crop shares in year $t - 1$ on the efficiency yield gap in year t . Therefore, further improvement of the current crop level analysis requires a detailed crop-specific dataset of different farms containing both input-output data and field specific information (e.g. previous crop, cropping sequence, tenure).

The general consensus that in developing countries an ‘intensification’ pathway is necessary to achieve food security and that in developed countries the (environmental) sustainability aspects are most relevant requires a more comprehensive understanding of the concept of resource use efficiency. One important aspect for Dutch arable farming not addressed in this article is the scope to improve resource use efficiency, and hence environmental and economic performance, through the reduction of input use without compromising crop yields (e.g. Ma et al., 2014; de Koeijer et al., 2002; Reinhard et al., 1999). Although most farms comply with the N application standards at crop level (Fig. 4) and at farm level (Fig. A4, see Supplementary Material), our results may suggest a potential to decrease the application of plant available N for many farms without reducing crop yields. The only two exceptions are spring onion and spring barley, crops for which the current N application standards may be too restrictive to allow farmers to achieve high yields and close yield gaps.

Further methodological improvements could be achieved through the application of linear programming to compute production trade-offs for alternative farmers’ objectives and under different scenarios. As an example, this could be implemented from an economic perspective through an optimization analysis in which P_{AEcon} is estimated under different input/output price ratios (e.g. Kanellopoulos et al., 2014; Jatoo et al., 2008) or from an environmental perspective in which the impact of different policies on P_{AEcon} is explored (building upon Lassaletta et al., 2014). The construction of trade-off curves is important to make explicit the yield penalty and environmental consequences associated with different management practices under specific objectives (Bos et al., 2016). Moreover, output distance functions considering multiple outputs and inputs at the farm level (Emvalomatis et al., 2011; Reidsma et al., 2009) can be estimated to study interactions between crops and between land, labour and capital and crop production, and to assess the magnitude and determinants of a ‘system-wide yield gap’ (Henderson et al., 2016).

6. Conclusion

Yield gaps of the most important arable crops cultivated in the Netherlands were decomposed into efficiency, resource and technology yield gaps (Silva et al., 2017). The crop level analysis focused on ware, seed and starch potato as well as sugar beet, spring onion, winter wheat and spring barley. Yield gaps were ca. 30% of potential yield (Y_p) for all crops, apart from starch potato and spring barley for which it was ca. 40%. We found that most of the yield gap is explained by the efficiency yield gap for ware potato and spring onion, by the resource yield gap for seed potato, by the technology yield gap for starch potato and by both the efficiency and technology yield gaps for sugar beet and cereals. The efficiency yield gap ranged between 9% (sugar beet) and 18% (spring onion and ware potato) of Y_p . The resource yield gap was less than 10% for all the crops and the technology yield gap ranged between 7% (ware potato) and 31% (starch potato). These results show that farmers are generally using technologies and input levels that allow them to reach Y_p and that further yield improvements, especially for ware and seed potato and spring onion, must be derived through better crop management practices as well as through improved crop rotations (and water management in case of starch potato and cereals). However, rotational effects tend to disappear when high input levels are applied, except when some pests (e.g. nematodes) cannot be controlled with plant protection agents.

The results regarding the effects of cropping frequency to crop yields were not very conclusive, partly due to scant information on crop rotations (e.g. cropping sequence) and confounding factors such as rented land. Yet, we consider the lack of clear effects of cropping frequency an interesting result because it shows that agronomic principles become obscured/muddled at ‘systems level’ given the interacting factors at crop rotation and farm level (e.g. economies of scope, financial situation of the farm, access to rented land). Significant differences in farm performance, but not in crop yields, were found across different farmers’ objectives. For instance, gross margin maximising, labour minimising and N use efficiency maximising farms can improve N production by about 17, 34 and 21%, respectively. Increasing N production at farm level needs to be achieved through increases in actual yields and through changes in the crop rotation plan. Further, there is potential to increase N use efficiency at crop and crop rotation level by reducing N inputs while maintaining crop yields.

Further research about the crop and farm level determinants of the efficiency yield gap is necessary to understand the underlying limiting factors to crop production in Dutch arable farms. For that purpose, a smaller sample of farms (e.g. Mandryk et al., 2014) must be monitored in-depth and over time. Improving the understanding of the efficiency yield gap may also provide operational insights for precision agriculture (e.g. Reidsma et al., 2015a). In addition, it seems necessary to develop and test suitable methodologies for the analysis of resource use efficiency at crop level to assess by how much input levels could be decreased without incurring yield losses as well as for disentangling the interactions between different crops and available resources at farm level.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.agsy.2017.06.005>.

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