Field Crops Research 249 (2020) 107755

Contents lists available at ScienceDirect

Field Crops Research

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

Disentangling genetic and non-genetic components of yield trends of Dutch forage crops in the Netherlands

R.L.M. Schils[a,b,*], W. Van den Berg[c], J.R. Van der Schoot[c,d], J.A.M. Groten[c], B. Rijk[a], G.W.J. Van de Ven[a], J.C. Van Middelkoop[d], G. Holshof[d], M.K. Van Ittersum[a]

[a] Plant Production Systems, Wageningen University, Droevendaalsesteeg 1, 6708 PB, Wageningen, the Netherlands
[b] Agrosystems, Wageningen Plant Research, Droevendaalsesteeg 1, 6708 PB, Wageningen, the Netherlands
[c] Field Crops, Wageningen Plant Research, Edelhertweg 1, 8219 PH, Lelystad, the Netherlands
[d] Animal Nutrition, Wageningen Livestock Research, De Elst 1, 6708 WD, Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Lolium perenne L.
Zea mays L.
Breeding
Yield gap
Management

ABSTRACT

Grass and forage maize are important forage crops in ruminant production systems in the temperate regions in northwest Europe. High yields of these crops contribute to farm profitability and local provision of feed, and hence local circularity of biomass and nutrients. Variety choice is an important option to raise potential and actual yields. We analysed 40 years of perennial ryegrass and 25 years of forage maize yield data from Value of Culture and Use (VCU) experiments to determine genetic and non-genetic trends of yields in time. For maize, we calculated an annual genetic trend of +173 kg DM ha^{-1} and a non-genetic trend of +65 kg DM ha^{-1}. Further analysis of the non-genetic trend showed that maize yields increased with increasing temperature sum during the growing season, and with earlier sowing. The feeding value of forage maize showed a genetic trend of +1.7 feed unit milk (VEM) kg DM^{-1} year^{-1}. The annual genetic gain of perennial ryegrass was +44 kg DM ha^{-1}. In the grass trials we found opposing non-genetic trends for cutting and grazing. Further analysis of the non-genetic trend showed that drought and the number of days with ground frost during the growing season had a negative effect on yield. We compared the average yields and trends in VCU trials with those of on-farm yields. The on-farm maize yields showed an annual trend of +195 kg DM ha^{-1}. We estimated an average realisation of the genetic gains of 75 % in farming practice, implying a widening gap between genetic potential and on-farm yields. Averaged over the entire period, on-farm maize yields were 4.6 t DM ha^{-1} (24%) lower than the yields of the VCU trials. The average annual on-farm grass yields did not show any trend, and were 1.6 t DM ha^{-1} (13%) lower than the yields of the VCU trials. In conclusion, our study revealed significant positive genetic and varying non-genetic trends in DM yields of forage maize and perennial ryegrass, the two dominant forage crops in the Netherlands. On-farm yields showed significant positive trends for forage maize, but no trend for grassland.

1. Introduction

The temperate regions in northwest Europe have relatively large areas of grassland and forage maize. Within the utilisable agricultural area, high proportions of grassland are present in Ireland (92 %), the United Kingdom (72 %) and the Netherlands (54 %), whereas the highest proportions of forage maize (11%–13%) are seen in Belgium, Germany, Luxemburg and The Netherlands. In those regions, farmers achieve high yields of grass (Smit et al., 2008) and forage maize (EUROSTAT, 2017). Currently, the average diet of dairy cows in the Netherlands contains 12 % fresh grass, 37 % conserved grass, 19 % forage maize and 32 % concentrates on a dry matter basis (CBS, 2018). As grass and forage maize are relatively cheap feed products compared to imported concentrates, a high on-farm production of forages and subsequent efficient conversion into milk improves farm profitability (Finneran et al., 2010) and enhances local circularity of biomass and nutrients.

Even though the current European grassland research agenda addresses a broad variety of ecosystem services, the traditional production function remains crucial in the context of global food security (Taube et al., 2014), due to the increasing demand for animal products. The yield potential of a specific crop depends on the local climate, soil properties and crop genotype (Van Ittersum and Rabbinge, 1997; Evans and Fischer, 1999). As climate and soil properties can hardly be

* Corresponding author at: Plant Production Systems, Wageningen University, Droevendaalsesteeg 1, 6708 PB, Wageningen, the Netherlands.
E-mail address: rene.schils@wur.nl (R.L.M. Schils).

https://doi.org/10.1016/j.fcr.2020.107755
Received 13 August 2019; Received in revised form 3 February 2020; Accepted 12 February 2020
Available online 25 February 2020

influenced, crop variety choice is the main management option to raise that yield benchmark. For perennial ryegrass, several European studies have been carried out to quantify annual genetic progress. In these studies, the annual genetic progress ranged from 0.25 % to 0.4 % (Wilkins and Mytton (2000); Chaves et al. (2009); Laidig et al. (2014); (Allerit, 1986); (Veronesi, 1991)). Studies of genetic progress in forage maize are less abundant. Laidig et al. (2014) and (Mackay et al., 2011) reported an annual genetic progress of 1.1 % and approximately 0.8 %, respectively.

The actual yield of crops is also determined by the non-genetic components environment and management (Van Ittersum and Rabbinge, 1997). Environmental factors include for example weather, soil and hydrology, while management factors include nutrient supply, crop protection, and in the case of grasslands grazing and cutting management. In Germany, Laidig et al. (2014) quantified the non-genetic trend as well, which they denoted as agronomic progress, which included all management and environment factors. For perennial ryegrass they calculated a negative annual agronomic trend of -0.29 %, which largely offset the genetic progress of 0.38 %. For forage maize they calculated a negative annual agronomic trend of -0.38 %.

This study addresses the question to what extent trends in yield and quality of forage maize and yield of perennial ryegrass in the Netherlands can be attributed to genetic and non-genetic components. We hypothesise that breeding efforts have improved yields and quality properties of forage crops. However, we expect that farmers have not been able to fully utilize these genetic gains, due to lagging uptake of new varieties and management factors. Therefore, the objective of our study was to analyse historical data of the VCU trials in the Netherlands to quantify genetic and non-genetic trends of perennial ryegrass yield and forage maize yield and quality, and to compare these with trends of on-farm yields. We also used the VCU trial yield data as a benchmark to assess on-farm crop performance by calculating the yield gap between both.

2. Methods

2.1. VCU experiments

New varieties are evaluated for their Value of Culture and Use (VCU) before they can be registered in the recommended or national list of varieties and released for commercial use. VCU testing of forage crops is carried out by Wageningen Research or its predecessors, under supervision of the Board for Plant Varieties. In this study we used data of forage maize (*Zea mays* L.), collected between 1991 and 2016, and perennial ryegrass (*Lolium perenne* L.), collected between 1975 and 2016 (Table 1). In total, there were around 1200 tested maize and grass varieties. In this study we only included the 187 maize and 174 grass varieties that were admitted to the Dutch recommended variety list. Each year, newly submitted varieties were sown for two or three consecutive years, alongside existing listed varieties.

The experiments were managed under good agricultural practices, implying adequate crop protection and nutrient supply from manure and mineral fertilizers according to agronomic recommendations and within environmental application standards. The actual manure and fertilizer application rates were not recorded in detail, but were close to the application rates of commercial dairy farms. Irrigation was only carried out incidentally, to prevent severe sward deterioration or complete harvest failures.

Table 1
Summary of features of VCU trials of forage maize and perennial ryegrass.

	Forage maize	Perennial ryegrass
Period	1991-2016	1975 - 2015
Experiments	208	84
Harvest years	1	3
Soil types	Clay/Loam - Sand	Clay/Loam - Sand
Varieties	187	174
Maturity	Early - Late	Late - Intermediate
Ploidy	–	Diploïd - Tetraploïd
Management	–	Cutting – Grazing
Traits	DM yield, Net energy for lactation	DM yield

All trials were laid out as an alpha-design (Patterson et al., 1978) in 2–3 replicates (forage maize) or 3–4 replicates (grass), and analysed as incomplete block design using the linear model facilities of Genstat (VSN International, 2017) with block as a fixed term. The size of the incomplete blocks was 5 or 6 plots. For forage maize the variety means per trial obtained from this analyses were the input for this study. The grass data were analysed per trial and harvest year and the obtained variety means were the input for this study.

2.1.1. Forage maize

The total dataset comprised 208 experiments of which 77 % were carried out on sandy soils and 23 % on clay or loam soils. Until 2011, early and late varieties were sown and harvested simultaneously in a single experiment, but from 2012 onwards, separate experiments were carried out for early and late varieties. The sowing dates varied from 19 April to 19 May, and harvest dates varied from 30 August to 31 October. At harvest, fresh yields were determined, and samples were taken for analysis of dry matter (DM) and Net Energy for Lactation (NEL) (Van Es, 1978). In the Netherlands, NEL is expressed as feed units milk (VEM = Voeder Eenheid Melk). One unit of VEM equals 6.9 kJ NEL.

2.1.2. Perennial ryegrass

Each year, one to three new grass trials were sown on different locations. The total dataset comprised 84 experiments of perennial ryegrass, of which 69 % were carried out on sandy soils and 31 % on clay or loam soils. Yields were recorded for three consecutive years, starting in the first full year after establishment. Separate experiments were carried out for cutting only (34 %) and mixed grazing and cutting (66 %). The majority of the experimental sites had separate experiments for intermediate and late varieties, while four experimental sites had only intermediate or only late varieties. The plots were harvested five to seven times per year. In grazing experiments, cows grazed for two to four days after the yield had been recorded. Grass from grazed plots was topped and removed after each grazing event. Even in the grazing experiments, silage cuts were carried out. Until around the year 2000 the second cut was harvested for silage and after 2000 the first cut was harvested for silage. At harvest, fresh yields were determined, and samples were taken for analysis of DM.

2.2. Farm data

Average annual on-farm DM yields between 1990 and 2016 were extracted from the national statistics database (CBS, 2018). This dataset comprises yield estimates of forage maize, as well as cut and grazed grassland, for two contrasting regions in the Netherlands: “south-east” representing predominantly dairy farms on sandy soils with a relatively high proportion of forage maize and “north-west” representing predominantly dairy farms on clay or peat soils with a relatively low proportion of forage maize. The net harvested yields of cut grass and forage maize were estimated through questionnaires and measurements of stored silage. The net intake of grazed grass was calculated on the basis of the difference between the energy demand for milk production, growth and maintenance, and the energy supply by grass silage, maize silage and concentrates. The gross yield of grassland was calculated from the net yield, assuming combined harvest, feeding and grazing losses of 20 %. The combined harvest and feeding losses of forage maize were fixed at 8% (1990–2006) or 5% (2007–2016). Feeding values (VEM) of ensiled forage maize were available between 2000 and 2015

(Schröder et al., 2016).

2.3. Weather data

Daily data of temperature, radiation, precipitation and Makkink evapotranspiration were collected from the closest available weather stations in the monitoring network of the Royal Netherlands Meteorological Institute (KNMI, 2016). The following parameters were calculated: temperature sum from the 1^{st} of January and from the start of the growing season with base temperatures of 0 °C, 5 °C and 8 °C, growing days (average temperature above 5 °C), frost days (minimum temperature below 0 °C), ground frost days (minimum temperature at 10 cm height below 0 °C), ice days (maximum temperature below 0 °C), and the accumulated precipitation surplus during the growing season. We used the lowest value of the accumulated surplus as a measure for drought.

2.4. Analytical framework

2.4.1. VCU experiments

The variety means were analysed with the mixed model facilities of Genstat using a model for genetic and non-genetic trends (Laidig et al., 2008, 2014; Piepho et al., 2014). For both crops we present the outcome in two steps. In the first step we assess a genetic and non-genetic trend. In the second step we add meteorological and management covariates to explore whether they explain the non-genetic trends. The exact application of the models for grass and forage maize differs slightly due to other experimental set-ups.

2.4.1.1. Forage maize. In (1a) y_{ijkt} is the mean yield or feeding value of maize genotype i on location j, in year k, in trial t and μ is the overall mean. G_i is the effect of genotype i (i = 1…187), Y_k is the effect of year k (k = 1991…2016) and L_j is the effect of location j. The terms $(GL)_{ij}$, $(GY)_{ik}$ and $(LY)_{jk}$ are the effects of the three two-way interactions. In twelve cases, two trials were carried out at the same location, which is described by the nested effect $(LT)_{jt}$. The three-way interaction GLY_{ijk} is comprised in the error term E_{ijkt}.

$$y_{ijkt} = \mu + G_i + L_j + Y_k + (GL)_{ij} + (GY)_{ik} + (LY)_{jk} + (LT)_{jt} + E_{ijkt} \tag{1a}$$

The fixed terms for the genetic trend G_i and non-genetic trend Y_k were estimated with (2a) and (3a). In (2a) β is a fixed regression coefficient, r_i is the first year of testing of variety i, and W_i models a random normal deviation of G_i from the genetic trend line. The oldest varieties were introduced in 1977, while the latest varieties were introduced in 2014. In (3a) γ is a fixed regression coefficient, t_k is a covariate for calendar year (1991–2015) and Z_k is a random residual component.

$$G_i = \beta r_i + W_i \tag{2a}$$

$$Y_k = \gamma t_k + Z_k \tag{3a}$$

All meteorological parameters were used in a model selection procedure using Genstat VSEARCH. The sowing date (ts) and tsum with base temperature 8 °C during the growing season (tsum8) had a significant effect on the response variates. In (4a) δ and θ are fixed regression coefficients for sowing date and tsum, respectively.

$$Y_k = \gamma t_k + \delta ts + \theta tsum8 + Z'_k \tag{4a}$$

For visualisation purposes the genotype and year means were saved from (1a) and regressed on their first year of testing or calendar year, respectively.

2.4.1.2. Perennial ryegrass. Most trial sites consisted of separate experiments with cutting and grazing management, and intermediate and late varieties. After sowing, the yields from the full harvest years 2, 3 and 4 were analysed. So yield is a repeated measurement on each variety within intermediate or late varieties within each trial. In (1b) y_{ijkth} is the mean yield of grass genotype i on location j, in year k, trial t, harvest year h and μ is the overall mean. G_i is the effect of genotype i (i = 1…174), Y_k is the effect of year k (k = 1975…2015) and Lj is the effect of location j. The terms $(GL)_{ij}$, $(GY)_{ik}$ and $(LY)_{jk}$ are the effects of the three two-way interactions. The three way interaction is comprised in the term $(GLY)_{ijk}$. Furthermore the two-way interaction effects of harvest with genotype $(GH)_{ih}$, location $(LH)_{jh}$, year $(YH)_{kh}$, and three-way interactions of harvest with genotype*location $(GLH)_{ijh}$, genotype*year $(GYH)_{ikh}$ and location*year $(LYH)_{jkh}$ were added. The term $(LT)_{jt}$, is the random effect of trial within location and $(LTG)_{jti}$ is the random effect of genotype within location and trial. The term $(LTH)_{jth}$ is the random contribution of harvest year h within trial within location. The term $(MY)_{bk}$ is the random effect of management b and year k. λ_m is the combined fixed effect of management, maturity and ploidy (m = 1…8), π_p is the fixed effect of the harvest year (h = 2, 3, 4) and κ_s is the fixed effect of soil type (s = clay, sand). Finally, the interaction $(GLYH)_{ijkh}$ is comprised in the error term E_{ijkth}.

$$\begin{aligned} y_{ijkth} = \mu &+ G_i + L_j + Y_k + (GL)_{ij} \\ &+ (GY)_{ik} + (LY)_{jk} + (GLY)_{ijk} + (GH)_{ih} + (LH)_{jh} + (YH)_{kh} \\ &+ (GLH)_{ijh} + (GYH)_{ikh} + (LYH)_{jkh} + (LT)_{jt} + (LTG)_{jti} \\ &+ (LTH)_{jth} + (MY)_{bk} + \lambda_m \\ &+ \pi_t + \kappa_s + E_{ijkth} \end{aligned} \tag{1b}$$

The fixed terms for the genetic trend G_i and non-genetic trend Y_k were estimated with Eq.s (2b) and (3b).

$$G_i = \beta r_i + W_i \tag{2b}$$

Where β is a fixed regression coefficient, r_i is the first year of testing of variety i, and W_i models a random normal deviation of G_i from the genetic trend line. The oldest varieties were introduced in 1942, while the latest varieties were introduced in 2012.

$$YEAR_k = \gamma t_k + Z_k \tag{3b}$$

Where γ is a fixed regression coefficient, t_k is covariate for calendar year, in the range 1975…2015. Z_k is a random residual.

A number of meteorological measurements was compiled for each trial. With model selection using Genstat procedure VSEARCH the lowest value of the accumulated precipitation surplus (drought) and the number of ground frost days in the growing season (frostdays) had a significant effect on the DM yield.

$$YEAR_k = \gamma t_k + \delta drought + \theta frostdays + Z'_k \tag{4b}$$

For visualisation purposes the genotype means were saved from model (1b) and regressed on their first year of testing. In the same way the management.year means were saved from model (1b) and regressed per management level on calendar year.

2.4.2. Farm data

Trends in on-farm yields were analysed with a regression model (5), where y_k is the average on-farm yield in year k, μ is the overall mean and ω is a fixed regression coefficient for calender year t_k.

$$y_k = \mu + \omega t_k + e_k \tag{5}$$

2.4.3. Yield gap

The yield gap was defined as the difference between the average variety yields in VCU trials and on-farm yields.

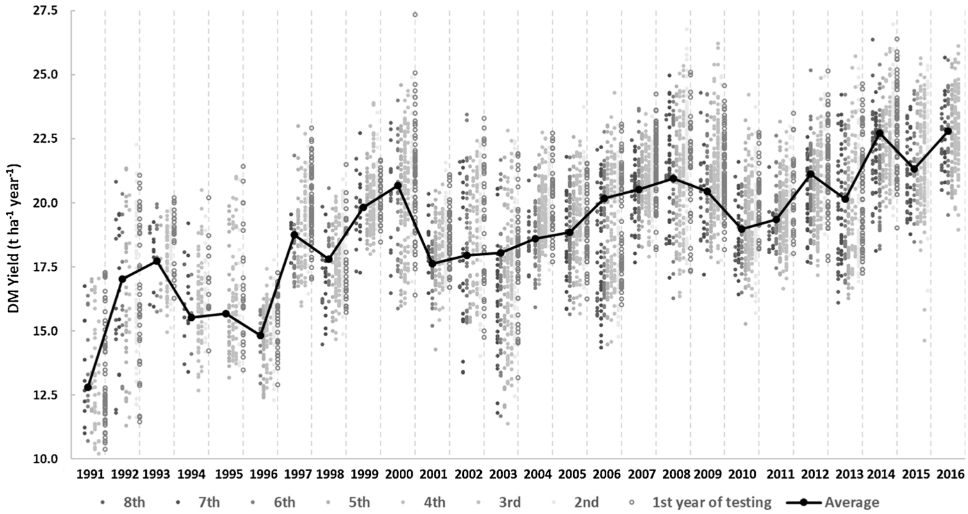

Fig. 1. Observed forage maize dry matter yields (t ha^{-1} year^{-1}) of listed varieties in VCU experiments, in relation to calendar year and year of testing.

3. Results

3.1. Forage maize

3.1.1. VCU experiments

The annual average DM yield of forage maize increased from 13.2 t ha^{-1} in 1991 to 22.9 t ha^{-1} in 2016 (Fig. 1, Fig. 4a). There was a large inter-annual variation as well as a wide intra-annual variation between individual varieties. In the same time frame, the average feeding value of forage maize increased from 902 to 994 VEM kg DM^{-1} (Fig. 4b), and the energy yield from 12.8–22.8 kVEM ha^{-1} (not shown).

The results of the basic model I (Eqs. 1a, 2a and 3a) showed a significant effect of the first year of testing of a variety (genetic trend) and a close to significant ($P < 0.068$) effect of calendar year (non-genetic trend) on the DM yield of forage maize (Table 2). The annual absolute genetic progress was estimated at 173 kg ha^{-1} which equates to a relative (compared to the overall mean) annual progress of 0.88 % (Fig. 2a). The non-genetic progress was 65 kg ha^{-1}, or 0.33 % per year (Fig. 2b). Feeding value and energy yield were only affected by the first year of testing, with an average genetic progress of 1.7 units of VEM (0.16 %) and 195 kVEM ha^{-1} (0.98 %), respectively.

Models II and III (Eqs. 1a, 2a and 4a) show that the non-genetic effect could be explained by adding date of sowing and temperature sum during growing season, for all three response variates. In model II the effect of calendar year was not significant for all three response variates when sowing date and temperature sum were included. Therefore, model III comprises first year of testing as parameter for genetic progress and sowing date and temperature sum as parameters for non-genetic progress. The estimate for first year of testing (genetic progress) was hardly affected by model choice. Sowing date had a negative effect on DM yield, feeding value and VEM yield. For each day of later sowing, the DM yield was reduced by 51 kg DM ha^{-1}, 0.55 VEM units and 65 kVEM ha^{-1} (model III). Given the range of 30 days between the earliest and latest sowing dates of the experiment, this matches a range of 1.53 t DM ha^{-1} year^{-1} or 16 units VEM. One unit of Tsum-degree during the growing season increased DM yield by 7 kg ha^{-1} and feeding value by 0.12 units of VEM. Given the approximate range of 400 degrees within the experiments, this matches a range of 3.1 t DM ha^{-1} year^{-1} or 53 units VEM.

3.1.2. Farm data

The average annual DM yield of forage maize increased from around 12 t ha^{-1} in 1990 to just above 16 t ha^{-1} in 2016, i.e. an annual increase of 195 kg ha^{-1} (Fig. 3). Yields in the northwest and southeast were mainly similar up to 2007 (not shown). Since then, DM yields in the southeast were consistently higher than in the northwest, on average 1.1 t DM ha^{-1}. The feeding quality also showed an increasing trend from around 900 VEM kg DM^{-1} in 1990 to around 1000 VEM kg DM^{-1} in 2016, an annual increase of 3.3 VEM kg DM^{-1}. Due to the increase of yield (1.4 % year^{-1}) and quality (0.35 % year^{-1}), the energy yield showed an even larger increase of 1.7 % year^{-1}.

3.1.3. Yield gap

The gap between the average yield in VCU-trials and on farms was

Table 2
Estimates of the regression parameters and standard errors in three models for forage maize (ns = not significant; * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$). Model I comprises Eqs. 1a, 2a and 3a, while models II and III comprise Eqs. 1a, 2a and 4a.

		DM yield (t ha^{-1})		VEM (kg DM^{-1})		VEM yield (t ha^{-1})	
Model	Parameter	Estimate	SE	Estimate	SE	Estimate	SE
I	Constant (μ)	19.360***	0.279	995***	4.445	19.899***	0.300
	First test year (r_i)	0.173***	0.008	1.712***	0.181	0.195***	0.009
	Calendar year (t_k)	0.065 ns	0.034	0.885 ns	0.498	0.063 ns	0.035
II	Constant (μ)	19.352 ***	0.257	995***	3.940	19.921***	0.253
	First test year (r_i)	0.173***	0.008	1.712***	0.181	0.195***	0.009
	Calendar year (t_k)	0.034 ns	0.032	0.325 ns	0.456	0.017 ns	0.032
	Sowing date (*ts*)	−0.051**	0.015	−0.540*	0.226	−0.065***	0.015
	Tsum (*tsum8*)	0.006**	0.002	0.122**	0.032	0.010 ***	0.002
III	Constant (μ)	19.311***	0.253	995***	3.778	19.882***	0.237
	First test year (r_i)	0.174***	0.008	1.743***	0.176	0.196***	0.008
	Sowing date (*ts*)	−0.051**	0.015	−0.549*	0.226	−0.065***	0.015
	Tsum (*tsum8*)	0.007***	0.015	0.128***	0.030	0.010***	0.002

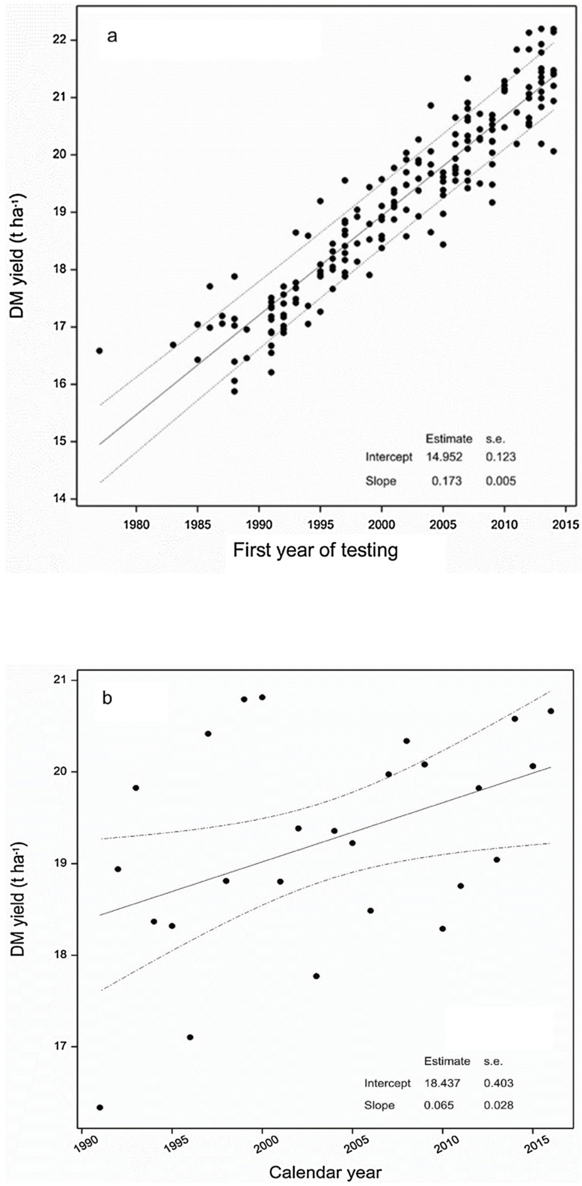

Fig. 2. Predicted values and 95 % probability range of variety DM yield of forage maize in relation to first year of testing (a) and annual DM yields in relation to calendar year (b), based on model I.

4.6 t ha^{-1}, varying from 1.7 to 6.6 t ha^{-1} (Fig. 4). The relative yield gap was 24 % (13–33 %). The yield gap increased by 51 kg DM ha^{-1} year^{-1}, but not significantly (t-probability = 0.071).

The average difference between feeding value in VCU trials and farm data was 30 VEM, with a large variation from -5 to 90. Note that this is a comparison between sampling fresh maize at harvest (VCU) and sampling ensiled maize (farms). The difference seems to become slightly smaller (0.9 VEM per year), but this is likely affected by the on-farm trend of harvesting at higher DM percentages, and thus lower feed quality losses during storage (Van Schooten et al., 2018).

3.2. Perennial ryegrass

3.2.1. VCU experiments

The annual average DM yield of perennial ryegrass was 12.5 t ha^{-1} in the period 1975–2015, with a large variation between 3.7 and 20.7 t ha^{-1} (Fig. 5) for individual varieties. The yields of the cutting trials were generally in the upper part of the yield range, and those of the grazing trials in the lower parts. This contrast between cutting and grazing, and the associated intra-annual variation was larger in the first half of the time period, up to circa 1990. Between 1990 and 2000 the average yields of both management regimes converged. The number of data points in the first ten years is relatively small as the number of submitted varieties per year was only between 5–10. After 1986, the number of submitted varieties increased to 20–40 per year.

The results of the basic model I (Eq.s 1b, 2b and 3b) showed significant effects of the first year of testing (genetic trend) on the DM yield of perennial ryegrass (Table 3). The annual absolute genetic progress was 44 kg ha^{-1} which equals a relative annual progress of 0.35 % (Fig. 6a). Calendar year (non-genetic trend) did not have significant effects, but the estimates indicated opposing trends for cutting and grazing trials; a negative trend of 31 kg DM ha^{-1} year^{-1} on the yields of the cutting trials and a positive effect of 34 kg DM ha^{-1} year^{-1} on the yield of the grazing trials (Fig. 6b).

Models II and III (Eqs. 1b, 2b and 4b) show that precipitation deficit and the number of ground frost days during the growing season had a significant effect on DM yield. Precipitation deficit was expressed as the minimal value of the accumulated precipitation surplus. It ranged from −233 mm (1976) to +15 mm (1984). One mm of additional shortage reduced the yield by 11 kg DM ha^{-1} year^{-1}. Given the range of nearly 250 mm, this matches a range of 2.8 t DM ha^{-1} year^{-1}. The number of ground frost days had an effect only on the yield of the cutting trials. It ranged from 14 to 45 days, and each additional day reduced the DM yield by 117 kg DM ha^{-1} year^{-1}, matching a range of 3.6 t DM ha^{-1} year^{-1}.

On average, the DM yields in cutting trials were consistently higher (2.3 t DM ha^{-1} year^{-1}) than those in grazing trials (Fig. 7). In the grazed trials, the DM yield of tetraploid varieties was significantly lower, 0.29 t DM ha^{-1} year^{-1}, than that of diploids. In the cutting trials, diploids and tetraploids had similar DM yields, but there was an additional three-way interaction: under cutting, intermediate diploids performed better than intermediate tetraploids, whereas late diploids and tetraploids had similar yields.

The average DM yields on clay soils, 13.81 t DM ha^{-1} year^{-1}, were significantly higher than those on sandy soils, 11.97 t DM ha^{-1} year^{-1} (not shown). The average DM yields in the first, second and third harvest year were 13.3, 13.1 and 12.8 t DM ha^{-1} year, with the third year yield significantly lower than the first year yield (not shown).

3.2.2. Farm data

Between 1990 and 2016, the average annual grass DM yield was 11.1 t ha^{-1}. The yields ranged between 9.2 and 13.1 t ha^{-1} (Fig. 8), without an overall significant trend. A closer look suggests a downward trend between 1990 and 2003, followed by an upward trend until 2016. The break around 2003 coincides more or less with an increasing divergence between the proportion of cut and grazed grass on Dutch farms, due to the reducing grazing time of the dairy herd. Between 1990 and 1996, the contribution of grazed grass to the total yield was slightly higher than that of cut grass. From around the year 2000 the contribution of cut grass was higher than that of grazed grass. Overall, the average DM yield of cut grassland increased annually with 140 kg ha^{-1}, while the DM yield of grazed grassland decreased by the same amount. In 2016, 75 % of the grassland yield was harvested as cut grass. The average DM yields and the contributions of cut and grazed grass to the total yield were almost similar in the northwest and southeast (not shown).

3.2.3. Yield gap

Between 1990 and 2015, the average annual DM yields of VCU experiments was 1.6 t DM ha^{-1}, or 13 %, higher than the actual on-farm yields (Fig. 9). The yield gap varied from negative values in some years to as much as 3.7 t DM ha^{-1}. The yields in the VCU experiments showed positive overall trends under grazing but negative overall trends under cutting. Overall the yields in the VCU experiments did not show a significant trend between 1990 and 2014.

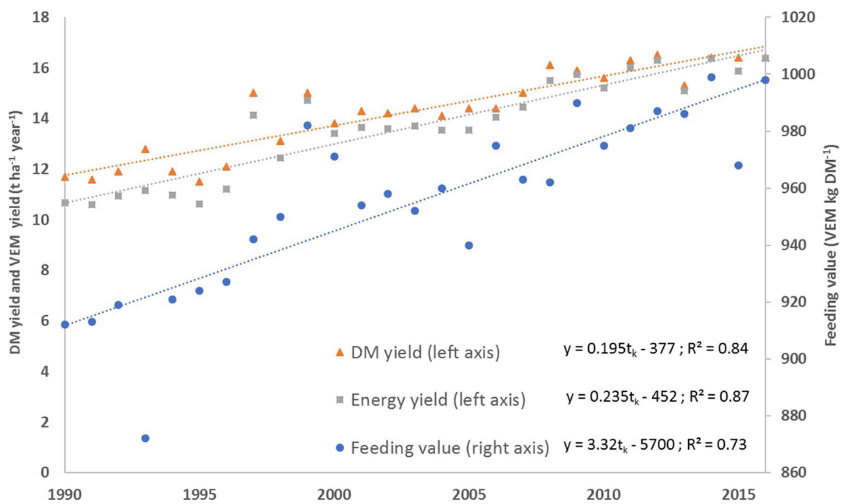

Fig. 3. Average annual on-farm DM yields (t ha^{-1}), feeding value (VEM kg DM^{-1}) and energy yield (t VEM ha^{-1}) of forage maize in the Netherlands.

4. Discussion

4.1. Methods and uncertainty

The setup of the experiments and the applied analytical framework allowed an estimation of genetic and non-genetic components of yield trends. We used the mixed model methodology of Piepho et al. (2014) in which the genetic and non-genetic trends are estimated directly by regression terms with random residuals, accounting for all the variation in these multi-year and -location experiments. Estimates of genetic

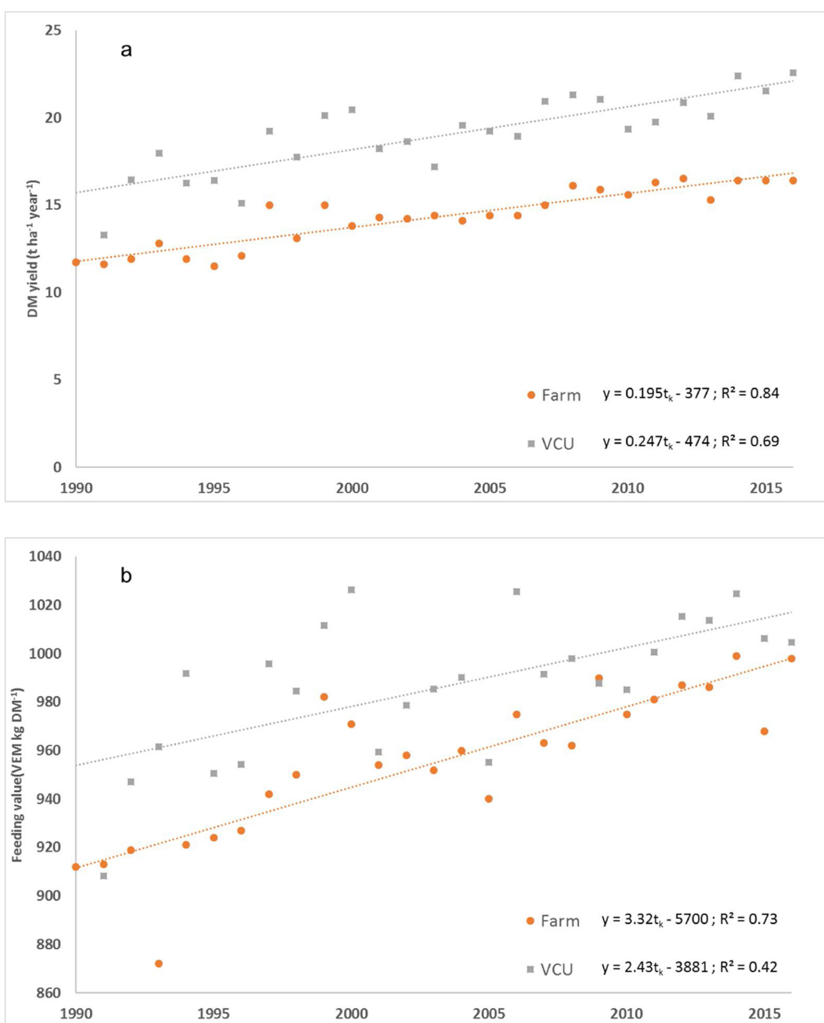

Fig. 4. Comparison between observed yield and quality of forage maize in VCU experiments and on farms: (a) average annual DM yields (t ha^{-1}), (b) feeding value (VEM kg DM^{-1}) in fresh harvest (VCU) or in silage (farm).

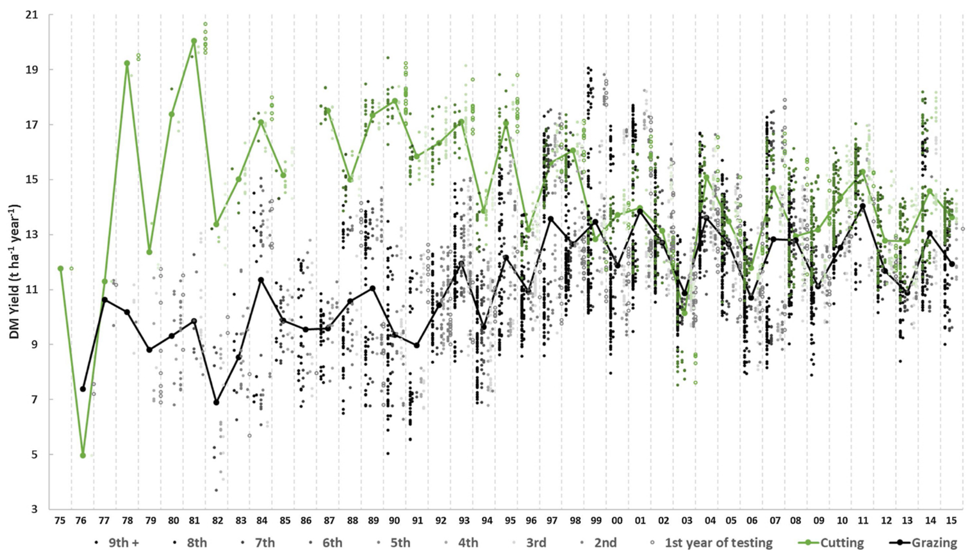

Fig. 5. Observed perennial ryegrass dry matter yields (t ha^{-1} year^{-1}) of listed varieties in relation to calendar year and year of testing; grazing (grey/black markers) and cutting (green markers) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 3
Estimates of the regression parameters and standard errors in three models for perennial ryegrass (ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.001). Model I comprises Eqs. 1b, 2b and 3b, while models II and III comprise Eqs. 1b, 2b and 4b.

Model	Parameter	DM yield (t ha^{-1})	
		Estimate	SE
I	Constant (μ)	15.438***	0.631
	First test year (r_i)	0.044***	0.002
	Calendar year.cutting (t_k)	−0.034ns	0.026
	Calendar year.grazing (t_k)	0.031ns	0.032
II	Constant (μ)	17.761***	0.914
	First test year (r_i)	0.044***	0.002
	Calendar year.cutting (t_k)	−0.043ns	0.031
	Calendar year.grazing (t_k)	0.021ns	0.025
	Lowest accumulated precipitation surplus (*drought*)	0.011***	0.003
	Number of ground frost days in the growing season.cutting (*frostdays*)	−0.114***	0.031
III	Constant (μ)	17.831***	0.923
	First test year (r_i)	0.044***	0.002
	Lowest accumulated precipitation surplus (*drought*)	0.011***	0.002
	Number of ground frost days in the growing season.cutting (*frostdays*)	−0.117***	0.031

progress in literature are either based on a similar mixed model approach, e.g. Laidig et al. (2014), or use a two-step approach in which varieties and years are first treated as fixed factors, and trends are then estimated with regression on calendar year and first year of testing, e.g. Mackay et al. (2011) or Rijk et al. (2013). Grassland experiments are generally multi-year experiments with repeated measurements over years (Piepho and Eckl, 2014), as is the case for our trials. Our model assumes a compound symmetry model for the interaction effects of harvest year with location and (location.trial). We analysed genotype means estimated separately for each harvest year and trial. We examined that the alternative approach does not improve the model fit.

In our study we aimed to further dissect the non-genetic trend in environmental and management factors. For forage maize we found two attributes, sowing date and temperature sum during the growing season that adequately replaced the calendar year trend. For grassland, two environmental attributes, i.e. precipitation surplus and ground frost during the growing season, contributed to the non-genetic trend. We believe there are two other important changes in management of grassland that we were unable to address correctly, but likely had an effect on the non-genetic trend.

First, nitrogen application changed considerably during the experiments as the VCU experiments roughly followed decreasing national trends. Although precise levels were not registered, we may assume a negative contribution of nitrogen application to the non-genetic trend of grass DM yield at some point between the mid-1990s and 2015. Taking a conservative estimate that the effective nitrogen application on grassland was reduced by 100 kg N, and assuming a response of 10 kg DM per kg N (Vellinga and André, 1999), we estimate a negative trend due to reducing nitrogen application of approximately 1 t DM ha^{-1} between the mid-1990s and 2015. For maize we expect a much smaller effect. Even though the nitrogen application on maize showed a significant decline since 1990, the effective nitrogen application was only marginally below agronomic recommendations of 180 kg N ha^{-1} year^{-1} in the most recent five years. A suboptimal nitrogen application of 10 % only reduces the DM yield by 1 or 2% (Schröder et al., 1998).

Second, changes in the cutting management of the grazing trials may have contributed to increasing yields. Until around the year 2000 the second cut was harvested for silage. Later, the first cut was harvested for silage. As cutting for silage takes place after a longer growing period and at relative high DM yields of 3–5 t DM ha^{-1}, using the first cut with its higher daily growth will increase the total annual yield (Schils et al., 2007b).

Random effects of trial location may have affected non-genetic trend estimates as trial locations changed throughout the experiments. For instance, the large contrast between cutting and grazing trials in the 1970s and early 1980s may partly be attributed to differences in location, i.e. soil quality and nitrogen input.

In grazing experiments, cows grazed for two to four days after the yield has been recorded. This grazing practice means during those days grass regrowth was reduced by the grazing activity, and thus not included in the recorded yield of the next cut. Assuming four to six grazing events per year, approximately 8–24 days of grass growth will have been affected by grazing.

In forage maize, the maturity groups were sown and harvested together until 2012. As all varieties, early and late, were harvested on the same day, they were not all harvested at the correct maturity stage. Too early harvest of late varieties may lead to underestimation of DM yield. Between 25 and 35 % DM, the effect on quality will be marginal. Too

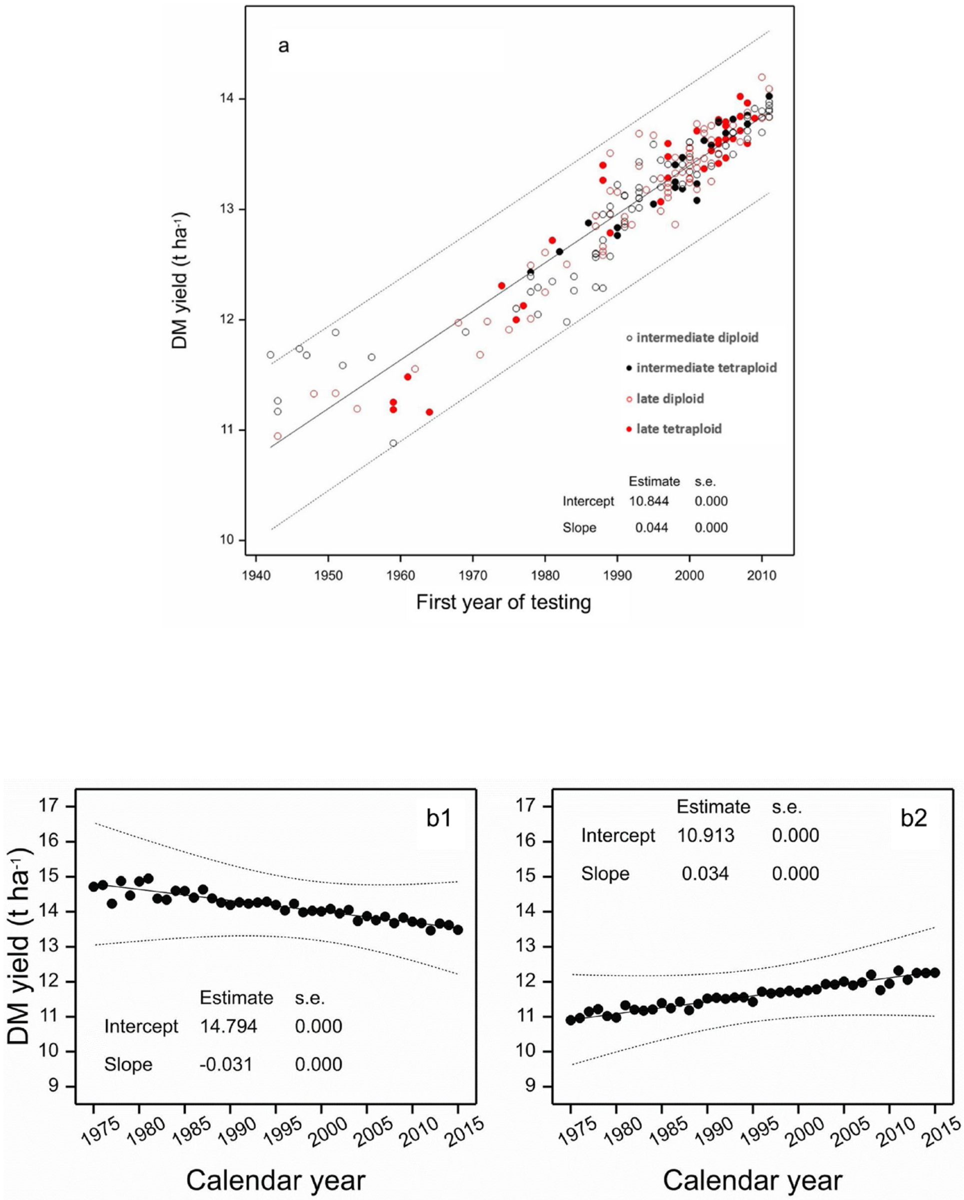

Fig. 6. Predicted values and 95 % probability range of the varieties of perennial rye grass DM yield in relation to first year of testing (a) and annual DM yields in relation to calendar year for cutting (b1) and grazing (b2), based on model I.

late harvest of early varieties may however lead to poorer feeding quality due to a higher susceptibility for fungal diseases, but on the other hand will not affect DM yields very much (Van Schooten et al., 2018).

The experimental set-up of this study does not allow an estimate of the effect of variety ageing as variety age and calendar year are confounded. Lower yields in ageing varieties are mainly caused by a gradual breakdown of disease resistance (Evans and Fischer, 1999). In the Dutch VCU trials, the forage maize and perennial ryegrass crops are not protected against fungal diseases. In German and British variety testing of cereals, the effect of variety age was estimated by comparison of untreated and fungicide treated plots (Mackay et al., 2011; Laidig et al., 2014). The importance of fungal diseases in forage crops is less than in grain cereals, but we cannot rule out effects of variety ageing in forage maize and perennial ryegrass.

Compared to the general farming practice, VCU experiments are located on relatively well managed farms on good soil types which may overestimate the yield gap with farming practice in the entire country. Furthermore, border effects in the experimental maize fields yields may have overestimated the yields compared to large fields in farming practice, but in this setup border effects through increased light interception only occurred along one of the short sides of each plot. All other three sides of the net plot were neighboured by a near-identical maize crop.

4.2. Genetic trend

For forage maize we found an annual genetic gain of 173 kg DM ha^{-1} (0.88 %). Comparable studies of genetic progress in forage maize are not abundant. Laidig et al. (2014) found an annual genetic progress of 192 kg DM ha^{-1} for Germany, quite similar to our estimate. An approximately similar value was mentioned by Reheul et al. (2017), citing unpublished data of Belgian variety trials. This is not surprising due to the vicinity of the dominant forage maize growing regions of Germany and Belgium. In the UK, Mackay et al. (2011) calculated a lower annual genetic progress of 109 kg DM ha^{-1}. In feeding quality we observed an annual genetic progress of 0.16 %. To our knowledge, this is the first study to report genetic progress in forage maize quality. Feeding quality

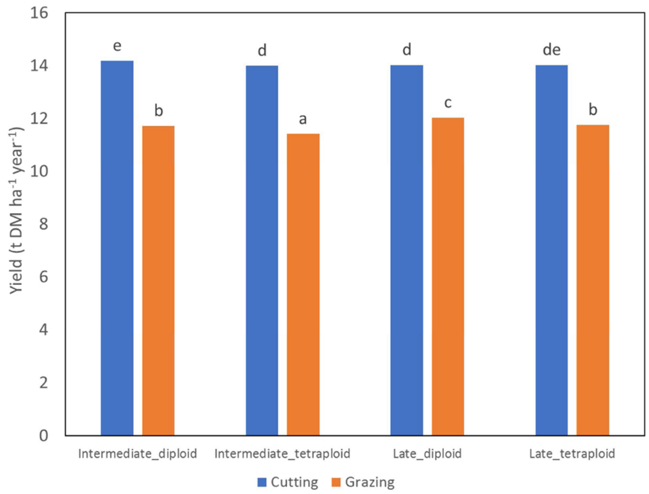

Fig. 7. Average DM yield of management, maturity and ploidy treatments (model I). Significant ($P < 0.05$) differences are indicated by different letters (a,b,c,d,e).

gained attention after the introduction of milk quota in 1984. Unpublished data of VCU trials show that between 1975 and 1985, the feeding quality decreased by 6%. From 1985 onwards, the feeding quality increased continuously. In 1992, the quality had reached again the level of 1975. The current feeding quality is now at +10 % compared to 1975, and +15 % compared to 1985.

For perennial ryegrass, we found an annual genetic gain of 44 kg DM ha^{-1} (0.35 %). Several other studies have been carried out to quantify annual genetic progress in perennial ryegrass. In the United Kingdom, Wilkins and Mytton (2000) calculated an annual progress of 0.4 % for perennial ryegrass. Chaves et al. (2009) reported an annual gain of 0.3 % in Belgian variety trials between 1966 and 2007. More recently, Laidig et al. (2014) found an annual genetic progress of 45 kg DM ha^{-1} or 0.38 % in German official variety trials (1983–2012). A slightly lower progress of around 0.25 % was observed for perennial ryegrass in France (Allerit, 1986) and Italy (Veronesi, 1991). We did not find interactions between management, ploidy or maturity on genetic progress. McDonagh et al. (2016) found a lower genetic progress under simulated grazing (0.35 %) than under cutting for silage (0.52 %). The authors hypothesised that this might reflect breeders selecting varieties with higher spring yields as those will benefit mostly from conservation management.

4.3. Non-genetic trend

We observed contrasting non-genetic trends for forage maize and grass. For maize, the weakly significant non-genetic trend was +65 kg DM ha^{-1} year^{-1}. The effect of calendar year could be substituted by temperature sum (Tbase = 8 °C) and date of sowing. In theory, sowing date and temperature sum could be confounded, as sowing date in part depends on temperatures in spring. In the VCU experiments however, there was no correlation between temperature sum and sowing date. The temperature sum, between sowing and harvest, showed a temporal and spatial gradient. Between 1990 and 2015, the temperature sum increased by 5.6 °C year^{-1}, and increased from north (52.97 N) to south (51.21 N) by 213 °C. The observed positive effect of temperature sum in the growing season on the yield of forage maize is not straightforward to understand as there may be confounding effects of increasing temperatures due to climate change and changes in the maturities of the tested varieties, i.e. a gradual shift towards earlier varieties. Higher temperatures increase the phenological development of maize, and thus reduce the length of the growing season and potentially the total dry matter production. Here, we have calculated the temperature sum for the actual growing season, from sowing to harvest. Therefore, the temperature sum of the growing season is a proxy for the positive effect of temperature on photosynthesis and dry matter production.

For grass we observed opposing non-genetic trends for grazing (+34 kg DM ha^{-1} year^{-1}) and cutting (-31 kg DM ha^{-1} year^{-1}). We hypothesise that this is partly affected by changes in nitrogen application, changes in management of the grazing plots, and trial location, as discussed earlier in the section on uncertainty (4.1). Furthermore we noticed a negative effect of drought and the number of ground frost days in the growing season. The effect of drought is not surprising and is documented abundantly (Norris, 1982; Jones, 2013). During cold conditions perennial ryegrass undergoes a hardening process that protects the plants against frost. Relative short periods of high temperatures may induce de-hardening (Kalberer et al., 2006), and subsequent frost events may damage plants (Eagles and Williams, 1992).

Non-genetic trends in other European studies show different outcomes. Laidig et al. (2014) calculated a negative annual trend of 34 kg DM ha^{-1} for perennial ryegrass in cutting trials, which is similar to our negative trend in the cutting trials. The non-genetic negative annual trend of 65 kg DM ha^{-1} for forage maize is remarkably different from our positive trend. A contrasting result of +108 kg DM ha^{-1} was found by Mackay et al. (2011).

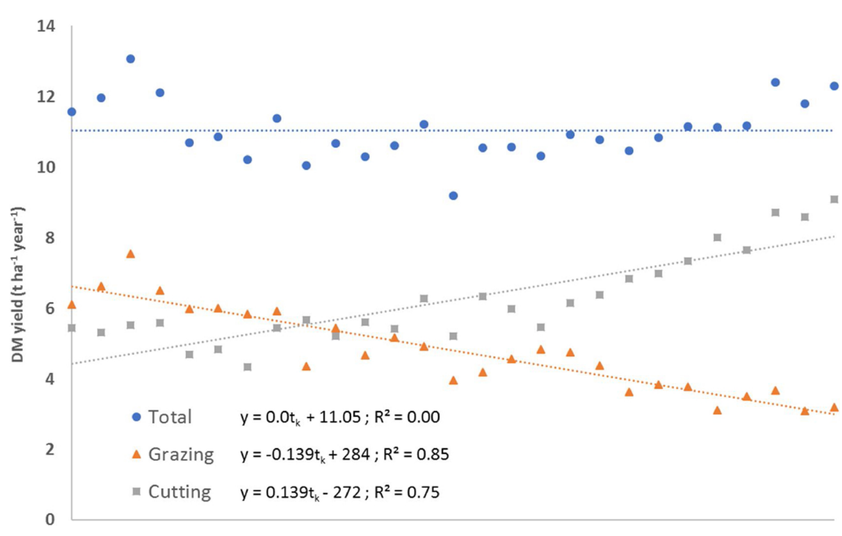

Fig. 8. Average annual on-farm yields (t DM ha^{-1}) of grass in the Netherlands (CBS, 2016).

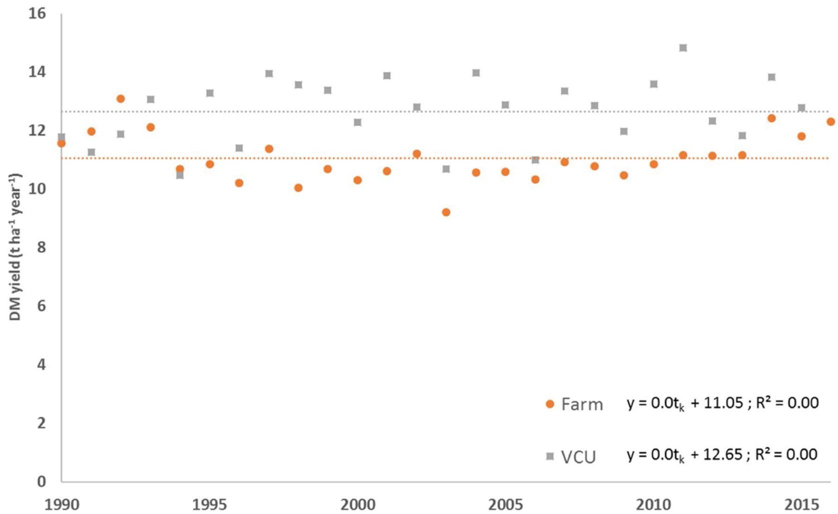

Fig. 9. Comparison between observed DM yield in VCU experiments (average of cutting and grazing trials) and on farms.

4.4. Trends in on-farm yields

On-farm forage maize yields in farming practice showed a positive trend of 195 kg DM ha^{-1}. If we assume that the non-genetic component is equal to the non-genetic trend in the VCU trials, we can calculate a genetic trend of 195 minus 65 equals 130 kg DM ha^{-1}, which is 75 % of the potential progress. It is not surprising that the realisation in practice is lower than 100 %, as variety choice by farmers is affected by many factors, other than yielding ability. The variety recommendations in the Netherlands are based on choices regarding maturity, disease risk, yield, and required feed quality in relation to milk production level. Furthermore farmers can stick to older varieties with which they had good experiences in previous years.

In farming practice, grass yields did not show any trend, but the same reasoning as above does not hold for grass as we cannot assume that the non-genetic trend will be similar in VCU trials and in practice. We have insufficient data about those trends to make a quantitative assessment. The annual genetic progress in perennial ryegrass of 44 kg DM ha^{-1} may be seen as a potential progress, under maximal uptake of new varieties. In reality, the average grassland renewal frequency in the Netherlands is approximately once every 5, 10 and 30 years on sand, clay and peat soils, respectively (Schils et al., 2007a). Therefore, the actual genetic progress will be 41, 38 and 25 kg DM ha^{-1} on sand, clay and peat soils, respectively. Finally, although perennial ryegrass is the main sown species, grass swards contain other sown or unsown species that affect DM yields.

4.5. Yield gap

We observed an average yield gap of 4.6 t DM ha^{-1} year^{-1} in forage maize. As the introduction of new varieties in practice lags at least three years behind, the benchmark needs to be lowered by 3*173 kg DM ha^{-1}, leaving a gap of approximately 4 t DM ha^{-1}. In grasslands, on-farm yields were 1.6 t DM ha^{-1} lower than the yields of the VCU trials. For both crops, the factors discussed in the previous sections such as partial uptake of new varieties, border effects and better soils for VCU trials, and diverse grassland management practices will contribute to the observed gap. Furthermore there is a wide range of production limiting and reducing factors, such as nutrient limitation, drought and flooding, soil compaction, sward deterioration, pests and disease incidence, and weed infestation. The yield gaps presented here are only a rough indication, due to the combination of factors that are inherently confounded with the differences in data between VCU trials and commercial farming. In our approach we took the average yield of varieties as the benchmark. Using instead the yield of the best varieties as a benchmark, would increase the yield gap. Furthermore, the yields in VCU trials are not a true potential yield as there may have been nitrogen input limitations or yield reductions due to pests and diseases. For a fair and more detailed comparison, further yield gap studies are needed that follow a specific protocol (Van Ittersum et al., 2013; Schils et al., 2018).

5. Conclusions

Analysis of the variety experiments revealed significant genetic gains in DM yields and quality of forage maize and DM yields of perennial ryegrass, the two dominant forage crops in the Netherlands. Positive non-genetic trends were observed in DM yields of forage maize, while for grass opposing non-genetic trends were observed for cutting and grazing. In forage maize, temperature sum and sowing date were responsible for the non-genetic yield trend. In perennial ryegrass, drought and ground frost during the growing season contributed to the non-genetic trend.

Analysis of on-farm data showed significant positive trends in forage maize yields, but no trend in grass yields. The average yields and the annual yield trends in farming practice were lower than those in VCU experiments. In forage maize, yield gaps were significantly increasing over time.

CRediT authorship contribution statement

R.L.M. Schils: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization, Project administration. **W. Van den Berg:** Methodology, Validation, Formal analysis, Data curation, Writing - review & editing, Visualization. **J.R. Van der Schoot:** Methodology, Formal analysis, Data curation, Writing - review & editing. **J.A.M. Groten:** Methodology, Formal analysis, Data curation. **B. Rijk:** Conceptualization, Writing - review & editing. **G.W.J. Van de Ven:** Conceptualization, Writing - review & editing. **J.C. Van Middelkoop:** Methodology, Writing - review & editing. **G. Holshof:** Methodology, Writing - review & editing. **M.K. Van Ittersum:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Jan Visscher, Henk Schilder, Gerrit Weijers and the staff at the experimental farms for managing the VCU experiments, as well as the farmers that facilitated the trials on their farms. This study is part of a public-private partnership research programme which was financed by Plantum, ZuivelNL, LTO, CUMELA, ForFarmers, Agrifirm, and the Ministry of Agriculture, Nature and Food Quality.

References

Allerit, R., 1986. Espéces fouragéres perennes: progrés réalises depuis 25 ans, apprécies à travers 11 expérimentation officielle. Fourages 107, 17–33.
CBS, 2018. Mest en Mineralen 2017. Centraal Bureau Statistiek, Voorburg p. 43.
Chaves, B., Vliegher, A.D., Waes, J.V., Carlier, L., Marynissen, B., 2009. Change in agronomic performance of Lolium perenne and Lolium multiflorum varieties in the past 40 years based on data from Belgian VCU trials. Plant Breed. 128, 680–690.
Eagles, C.F., Williams, J., 1992. Hardening and dehardening of Lolium perenne in response to fluctuating temperatures. Ann. Bot. 70, 333–338.
EUROSTAT, 2017. Crop Production in EU Standard Humidity. [apro_cpsh1]. .
Evans, L.T., Fischer, R.A., 1999. Yield potential: its definition, measurement, and significance. Crop Sci. 39 (6), 1544–1551.
Finneran, E., Crosson, P., O'Kiely, P., Shalloo, L., Forristal, D., Wallace, M., 2010. Simulation modelling of the cost of producing and utilising feeds for ruminants on irish farms. Journal of Farm Management 14, 95–116.
Jones, M., 2013. The Grass Crop: the Physiological Basis of Production. Springer Science & Business Media p. 369.
Kalberer, S.R., Wisniewski, M., Arora, R., 2006. Deacclimation and reacclimation of cold-hardy plants: current understanding and emerging concepts. Plant Sci. 171, 3–16.
KNMI, 2016. Daily Weather Data 1975-2015. Royal Netherlands Meteorological Institute. www.knmi.nl.
Laidig, F., Drobek, T., Meyer, U., 2008. Genotypic and environmental variability of yield for cultivars from 30 different crops in German official variety trials. Plant Breed. 127, 541–547.
Laidig, F., Piepho, H.P., Drobek, T., Meyer, U., 2014. Genetic and non-genetic long-term trends of 12 different crops in German official variety performance trials and on-farm yield trends. Theor. Appl. Genet. 127, 2599–2617.
Mackay, I., Horwell, A., Garner, J., White, J., McKee, J., Philpott, H., 2011. Reanalyses of the historical series of UK variety trials to quantify the contributions of genetic and environmental factors to trends and variability in yield over time. Theor. Appl. Genet. 122, 225–238.
McDonagh, J., O'Donovan, M., McEvoy, M., Gilliland, T.J., 2016. Genetic gain in perennial ryegrass (Lolium perenne) varieties 1973 to 2013. Euphytica 212, 187–199.
Norris, I., 1982. Soil moisture and growth of contrasting varieties of Lolium, Dactylis and Festuca species. Grass Forage Sci. 37, 273–283.
Patterson, H.D., Williams, E.R., Hunter, E.A., 1978. Block designs for variety trials. J. Agric. Sci. 90, 395–400.
Piepho, H.P., Eckl, T., 2014. Analysis of series of variety trials with perennial crops. Grass Forage Sci. 69 (3), 431–440.
Piepho, H.P., Laidig, F., Drobek, T., Meyer, U., 2014. Dissecting genetic and non-genetic sources of long-term yield trend in German official variety trials. Theor. Appl. Genet. 127, 1009–1018.
Rijk, B., van Ittersum, M., Withagen, J., 2013. Genetic progress in Dutch crop yields. Field Crops Res. 149, 262–268.
Schils, R., Aarts, H., Bussink, D., Conijn, J., Corre, V., Van Dam, A., Hoving, I., Van Der Meer, H., Velthof, G., 2007a. Grassland renovation in the Netherlands; Agronomic, environmetal and economic issues. Grassland Resowing and Grass-arable Crops Rotations. PRI, pp. 9–24.
Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C., Zom, R.L.G., 2007b. DairyWise, a whole-farm dairy model. J. Dairy Sci. 90, 5334–5346.
Schils, R., Höglind, M., Middelkoop, Jv., Holshof, G., Verloop, J., Rijk, B., Ven, G., Berg, W., Van der Schoot, J., Van Ittersum, M., 2018. Framework for yield gap analysis in grasslands. Sustainable meat and milk production from grasslands. In: Proceedings of the 27th General Meeting of the European Grassland Federation, Cork, Ireland, 17–21 June 2018. Teagasc, Animal & Grassland Research and Innovation Centre. pp. 90–92.
Schröder, J., Neeteson, J., Withagen, J., Noij, I., 1998. Effects of N application on agronomic and environmental parameters in silage maize production on sandy soils. Field Crops Res. 58, 55–67.
Schröder, J.J., Velthof, G., Van Bruggen, C., Daatselaar, C., De Koeier, T., Prins, H., Wolswinkel, K.J., 2016. Ontwikkeling van gewasopbrengsten in relatie tot gewijzigde gebruiksnormen – Ex post vraag 8, Evaluatie Meststoffenwet 2016. Wageningen Plant Research p. 30.
Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use in Europe. Agric. Syst. 98, 208–219.
Taube, F., Gierus, M., Hermann, A., Loges, R., Schönbach, P., 2014. Grassland and globalization – challenges for north-west European grass and forage research. Grass Forage Sci. 69, 2–16.
Van Es, A., 1978. Feed evaluation for ruminants. I. The systems in use from May 1977-onwards in The Netherlands. Livest. Prod. Sci. 5, 331–345.
Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Res. 143, 4–17.
Van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Res. 52, 197–208.
Van Schooten, H., Philipsen, B., Groten, J., 2018. Handboek Snijmaïs. Wageningen Livestock Research p. 208.
Vellinga, T.V., André, G., 1999. Sixty years of Dutch nitrogen fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and of developments in time. NJAS Wageningen J. Life Sci. 215–241.
Veronesi, F., 1991. Achievements in Fodder Crop Breeding in Mediterranean Europe. Fodder Crops Breeding: Achievements, Novel Strategies and Biotechnology, Wageningen (Netherlands) 18-22 Nov 1990. Pudoc. p. 230.
VSN International, 2017. Genstat for Windows, 19th edition. VSN International, Hemel Hempstead, UK Web page: Genstat.co.uk.
Wilkins, Allen, Mytton, 2000. Differences in the nitrogen use efficiency of perennial ryegrass varieties under simulated rotational grazing and their effects on nitrogen recovery and herbage nitrogen content. Grass Forage Sci. 55, 69–76.