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RESEARCH ARTICLE

Reducing competition in forage maize intercropped with tall fescue through herbicides, plant types, and sowing density

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Abstract

Forage maize is the predominant crop in the intensive dairy farming regions of Europe. This crop, however, is associated with considerable nitrate leaching and decreasing soil organic matter concentrations. Catch crops installed after maize harvest can usually only be sown late in the growing season in North-West Europe to tackle these problems efficiently. Intercropping maize with grass species such as tall fescue has the potential to result in a timely developed grass sward before the winter, capable of assimilating important quantities of carbon and soil residual nitrogen and to buildup soil organic matter. Yet, the intercropped grass might compete with the maize for water and nutrients. Here, we report, for the first time, the effect of (i) herbicide combinations, (ii) tall fescue sowing density and method, (iii) tall fescue morphotype, and (iv) the maize maturity group on the functioning of forage maize intercropped with tall fescue. We assessed maize and intercropped tall fescue yields and studied the N uptake and the effect on soil residual nitrate of the intercropped grass. We found that every kg dry matter ha^{-1} of tall fescue aboveground dry matter, present at the end of the autumn, came at a cost of 1.4 kg dry matter ha^{-1} of maize dry matter yield. Herbicide treatments can regulate grass-maize competition, whereas lower sowing densities of the intercropped grass or different sowing methods of the intercropped grass had no effects. Despite the superior winter growth of the Mediterranean tall fescue morphotype compared to the continental tall fescue, the reduction in soil residual nitrate was similar for both morphotypes. We demonstrate that tall fescue intercropped in maize can be an alternative to cover crops installed after the harvest of maize, to reduce nitrate leaching, and to compensate for the soil organic matter losses associated with forage maize production.

Keywords Italian ryegrass · Cover crop · Catch crop · Mediterranean tall fescue · Roots · Herbicides

1 Introduction

Intensive dairy farms in the North-West of Europe rely predominantly on two crops: grass and forage maize. Maize is praised for its high and stable yields and its high energy content makes it a perfect complement for protein-rich grass (-clover) in the rations of dairy cows (Reheul et al. 2017). A drawback of the high share of forage maize in the crop rotation is the winter leaching of nitrate nitrogen (NO_3-N), polluting the groundwater (Wachendorf et al. 2006). Moreover, forage maize results in a net decrease of soil organic matter (SOM) concentrations. Based on a survey of 31 Belgian fields on which forage maize was grown for at least 13 years in the 15 years preceding the sampling, soil organic carbon (SOC) measured in the 0–0.3-m soil layer decreased from 1.86 to 1.60 % in the period 1990–2018 (Xu 2018). Similar problems occur in regions throughout the world where maize is a predominant crop, like, for example, in the North-Central United States corn belt region (West et al. 2020).

Catch or cover crops can reduce both the loss of nutrients and the decline of SOM associated with growing forage maize. Where the growing season is sufficiently long, double cropping of maize with another crop for example barley–maize system in Spain (Maresma et al. 2019) can increase the nitrogen recovery. In North-West Europe, where forage maize is harvested from mid-September until end-October, Italian ryegrass (*Lolium multiflorum* Lam.) and winter rye (*Secale cereale* L.) cover crops offer the best perspectives to take up significant amounts of N (Thorup-Kristensen et al.

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2003). However, their N uptake is very variable mainly depending on their sowing date and the weather conditions. Based on 6 years of data from the Netherlands, Schröder et al. (1996) found that the aboveground N uptake of catch crops in combination with continuous maize cropping varied from 50–70 kg N ha^{-1} in mild winters to less than 10 kg N ha^{-1} in cold winters. Komainda et al. (2016) found that in the North of Germany, winter rye catch crops after maize required a temperature sum (base 5 °C) of 278 °C·d to achieve an agronomically relevant N uptake of 20 kg N ha^{-1}, which corresponds to sowing the rye, the latest, in mid-September. At that time, however, only the earliest-maturing maize varieties have the required dry matter content of 30–35 % to make proper maize silage. As early-maturing varieties are about 5–10 % less productive than later-maturing varieties, adopting a strategy to avoid N losses using earlier varieties in combination with catch crops implies a potential yield loss (Reheul et al. 2017).

A strategy to overcome these shortcomings of catch crops sown after maize is to intercrop the catch crop in the developing maize. Perennial ryegrass (*Lolium perenne* L.) sown in the North of Germany between the maize rows at a density of 6 kg ha^{-1} when the maize had 3–4 leaves took up on average 60 kg N ha^{-1} in the shoots and roots (Wachendorf et al. 2006). In the Netherlands, the advice is to undersow the maize when it has reached a height of ca. 0.5 m (5–6-leaf stage) with Italian ryegrass at a density of 25 kg ha^{-1} (Van Schootenen et al. 2019). Sowing can be done in combination with hoeing or using a seed drill where pipes corresponding to the maize rows are lifted. In practice, however, this technique is not easy to implement as the ideal sowing time interval is rather short and the result is weather dependent (Hilhorst and Verloop 2014).

A second option is to install maize in a living grass sward. Yet, maize sown in a living mulch of Italian ryegrass in Switzerland, for instance, suffered from intense competition. This resulted in important yield losses: even with a N fertilization of 250 kg N ha^{-1}, the maize yield decreased by 15 % compared to the control (Garibay et al. 1997).

A third strategy is to sow maize and grass simultaneously, i.e., to intercrop the maize with grass (sensu Malézieux et al. 2009), which is the study object of the present paper (Fig. 1). Compared to undersowing grass in the developing maize, a simultaneous establishment usually allows a better start for the grass and there is no extra workload since machinery is available to simultaneously sow both maize and grass.

To reduce the competition between maize and the intercropped grass, it is necessary to use a grass species with a slow initial growth after sowing. Ryegrasses (*Lolium* sp.) are therefore much less suitable than, e.g., fescues (*Festuca* sp.). Manevski et al. (2015) intercropped maize with red fescue (*Festuca rubra* L.) on sandy soils in Denmark and concluded that intercropping could reduce nitrate leaching without significant maize yield loss. Tall fescue (*Festuca arundinacea* Schreb.) also is a potential candidate for intercropping in maize owing to its slow establishment but high yield potential once established (Cougnon et al. 2014) and its deeper rooting (Cougnon et al. 2017) than perennial ryegrass. Moreover, it is a species with a large intraspecific variation with three morphotypes (Hand et al. 2012): (i) the continental type which is native throughout Europe, (ii) the Mediterranean type which is native to Northern Africa, and (iii) the rhizomatous type which originates from the Iberian Peninsula. Within the continental type, numerous forage and turf cultivars were created. The former are selected to maximize production; the latter grow less vigorously, making them good candidates for intercropping. Compared to the continental morphotype, the Mediterranean morphotype is characterized by a summer dormancy (Norton et al. 2006) which may result in a reduced competition during the growing period of the maize while their autumn and winter activity (Dierking and Kallenbach 2012) may result in an increased uptake of soil residual nitrate and biomass yield.

The objectives of the present study were

1. To quantify yield loss in forage maize intercropped with tall fescue due to competition.

Fig. 1 Maize intercropped with tall fescue. Left: development of maize and a continental turf-type of tall fescue on 18/06/2015; sown on 28/04/2015 at 15 kg ha^{-1}. Right: maize intercropped with a Mediterranean forage-type of tall fescue, at harvest on 01/09/2020.

2. To quantify the effects of (i) herbicide applications, (ii) sowing density of the intercropped tall fescue, (iii) the sowing method, (iv) the morphotype of the undersown tall fescue, and (v) the maize maturity group on this competition.
3. To test the hypothesis that intercropping forage maize with tall fescue is an alternative to Italian ryegrass cover crops sown after maize harvest in terms of grass biomass production, N uptake, and soil residual nitrate reduction.

2 Materials and methods

2.1 Experimental site, trial designs, and crop husbandry

A series of field trials were established in the period 2014–2019 at the experimental farm of Ghent University in Melle (50.9° N, 3.8° E) and one trial in 2016 on a dairy farm in Assenede (51.2° N, 3.7° E). The soils at both locations are cambisols with a sandy loam texture; pH and SOC were in the range 6.1–6.5 and 1.1–1.4 %, respectively. The different trials are identified with a unique code where the letter stands for the trial location (M for Melle, A for Assenede) followed by the sowing year of the trial (14 for 2014 etc.). There are three groups of trials (Table 1): (i) M14, M15, and M16 focused on herbicide use to reduce tall fescue competition; (ii) A16, M17, and M18 focused on sowing density, sowing method, and morphotype of the tall fescue as a means to reduce tall fescue competition; and (iii) M19 focused on the effect of maize maturity group.

The husbandry of all these trials was similar. The trials were established on a new part of arable land every year; the preceding crops were either maize or cereals followed by a cover crop. Fertilization was applied according to the legal threshold. In the beginning of April, cattle slurry corresponding to circa 120 kg N ha^{-1}, 80 kg P_2O_5 ha^{-1}, and 220 kg K_2O ha^{-1} was incorporated in the soil. After plowing, 50 kg N ha^{-1} from calcium ammonium nitrate (270 g N kg^{-1}) was applied and the seedbed was prepared using a rotary harrow. Sowing of grass and maize took place on the same day between 19th of April in M17 and 13th of May in M16 (dates given in Table 3). The maize was sown in rows spaced by 0.75 m at a density of 114,000 seeds ha^{-1} using varieties from the early-intermediate maturity group (commercial FAO number 200-240) ("Sue" in M14, M15; "LG31.218" in M16, M17, M18; "Sumaris" in A16) and either early "Resolute" (FAO 180) or intermediate "LG31272" (FAO 235) in M19. Weed management was conducted with herbicides (Table 2). They were applied in the 3–5 leaves stadium of the maize. In trials M14, M15, and M16, different herbicide treatments were compared, whereas in the remaining trials, the whole trial received the same treatment. Further details regarding sowing methods, sowing densities, varieties of the intercropped grass, and herbicide treatments are given below in the description of the specific trials.

Trials M14, M15, and M16 compared the effect of different herbicide treatments on the development of tall fescue and on the yield of maize. These herbicide trials were established as a randomized complete block design with three replicates and five treatments; individual plots measured 6 m × 10 m. In each block, four of the five maize plots were intercropped with tall fescue and treated with different herbicide mixtures (A, B, C, D: Table 2). Treatment A was recommended for maize intercropped with tall fescue (Barenbrug 2015) and treatments B and D were designed to control a broad range of dicotyledonous weeds in maize with low and high activity against *Festuca* grasses, respectively, whereas treatment C was chosen to affect only dicot weeds. The fifth plot was a maize monocrop treated with herbicide treatment A. The grass in these trials, a mixture of continental turf-type tall fescue varieties "BarlexasII" (90 % of seed mass) and "Barleroy" (10 % of seed mass) commercialized as "Proterra maize" (Barenbrug, the Netherlands), was sown a few hours before the maize at a density of 15–20 kg ha^{-1} using a 2.5-m mechanical seed drill with 19 coulters at a depth of 2–3 cm.

Trials A16, M17, and M18 compared the effect of the tall fescue sowing density, sowing method, and morphotype on grass and maize yields. These trials were set up as randomized complete block designs with an individual plot size of 6 m ×

Table 1 Overview of the studied maize with intercropped tall fescue trials.

Trial	Location	Period	Research subject
M14	Melle	2014–2015	Herbicide treatments
M15	Melle	2015–2016	Herbicide treatments
M16	Melle	2016–2017	Herbicide treatments
A16	Assenede	2016–2017	Tall fescue sowing density, seed distribution, and morphotype
M17	Melle	2017–2018	Tall fescue sowing density, seed distribution, and morphotype
M18	Melle	2018–2019	Tall fescue sowing density, seed distribution, and morphotype
M19	Melle	2019–2020	Maize maturity group

Table 2 Herbicide application dates, active ingredients, and doses for seven trials studying maize intercropped with tall fescue.

Trial	Date	Active ingredient and dose (g ha^{-1})
M14	28/05/2014	A: tembotrione (88) + S-metolachlor (624) + terbuthylazine (375)
M15	28/05/2015	B: tembotrione (44) + dimethenamid-P (280) + terbuthylazine (250) + topramezone (33.6)
M16	08/06/2016	C: pyridate (900) + dicamba (240) + tritosulfuron (50)
		D: sulcotrione (300) + dimethenamid-P (720) + nicosulfuron (21)
A16	07/06/2016	Tembotrione (44) + dimethenamid-P (280) + terbuthylazine (250) + dicamba (90)+ tritosulfuron (18.8)+ topramezone (50.4)
M17	18/05/2017	Tembotrione (44) + dimethenamid-P (280) + terbuthylazine (250) + pyridate (900)
	30/05/2017	Sulcotrione (300) + dicamba (120) + tritosulfuron (25)
M18	04/06/2018	Mesotrione (100) + dimethenamid-P (720) + dicamba (240) + tritosulfuron (50)
M19	04/06/2019	Mesotrione (120) + dimethenamid-P (720) + dicamba (240) + tritosulfuron (50)

10 m and with three replicates. Each block included five treatments, a maize monocrop and four intercropping treatments:

1. Continental turf-type broadcast at 15 kg ha^{-1} (Broad 15 kg ha^{-1} Cont.)
2. Continental turf-type broadcast at 7.5 kg ha^{-1} (Broad 7.5 kg ha^{-1} Cont.)
3. Continental turf-type interrow-sown at 15 kg ha^{-1} (Inter 15 kg ha^{-1} Cont.)
4. Mediterranean forage-type broadcast at 15 kg ha^{-1} (Broad 15 kg ha^{-1} Med.)

The broadcast sowing was done by hand. Seeds were incorporated in the soil by harrowing followed by the maize sowing. The interrow seeding was done immediately after the maize sowing: three rows spaced by 0.15 m were sown centrally between the maize rows using a single row seeder (Wintersteiger, Austria) in such a way that the distance between a maize row and the nearest grass row was 0.225 m. The continental turf-type was the mixture "Proterra maize" (see above); the forage-type Mediterranean tall fescue was the variety "Prosper" (Barenbrug, the Netherlands).

Trial M19 compared maize and grass yields and soil residual nitrate of maize intercropped with tall fescue versus monocropped maize followed by a catch crop for two maize maturity groups. The trial was set up as a split plot design with maize variety (early-maturing variety; intermediate-maturing variety) as main plot factor and grass (Mediterranean tall fescue as an intercrop; Italian ryegrass catch crop after a maize monocrop; no grass catch crop after maize monocrop) as subplot factor. Subplots measured 6 m × 10 m. This trial allowed us, among others, to compare two alternatives to reduce nitrate leaching in forage maize production: an early maize variety grown as a monocrop (harvested early September), followed by a cover crop of Italian ryegrass or an intermediated maize variety (harvested early October) intercropped with tall fescue. Both the maize and the Mediterranean tall fescue ("Prosper" at 15 kg ha^{-1}) were sown on 9th of May 2019; harvest date was 9th of September 2019 for the early maize variety ("Resolute"; FAO 180) and the 3rd of October for the intermediate maize variety ("LG31272"; FAO 235). Within 1 day after the maize harvest, the respective subplots "maize monocrop followed by a catch crop" were broadcast sown with Italian ryegrass ("Madlen" at 40 kg ha^{-1}).

In A16, M17, M18, and M19, the whole trial received the same herbicide treatment (Table 2). Based on the experience gathered in M14–M16, we excluded nicosulfuron because it was found to be lethal for the grass, even at reduced doses. Based on the work of De Zutter (2017), we applied dimethenamid-P at a dose that suppressed the development of the intercropped tall fescue, without being lethal to it. Herbicides to tackle dicots were used according to the manufacturers' recommendations. Due to the very dry conditions in the spring of 2017, the weed control after the first treatment (18th of May) was unsatisfactory and a second treatment (30th of May) was necessary 2 weeks later (Table 2).

2.2 Crop and soil measurements

As soon as the maize reached a whole-crop dry matter (DM) content of 30–35 % (corresponding to stage 85 on the BBCH scale), 6 m^2 of each plot was harvested manually (dates given in Table 3). The harvested plants were weighed; a sample of ten complete plants (stem + cobs) was chopped and a subsample of circa 500 g was dried (16 h at 80 °C and 4 h at 105 °C) and weighed again to calculate the total plant maize dry matter yield. All maize yields reported in this paper are total aboveground plant dry matter yields. Within a few days after the manual harvest of the center of the plots, the remaining maize was harvested with a forage harvester with an eight-row front attachment (Orbis 600, Claas, Germany). The design of the trial was such that both the harvester and the trailer following the harvester were driving just once over each plot. In M18, maize yield was not measured due to the presence of lodging

Table 3 Dates of maize sowing, harvest, and sampling of the aboveground grass biomass, soil residual nitrate, and grass root biomass in maize-tall fescue intercrops differing in sowing method: drilled (drill), broadcast (broad), or interrow-sowing (inter). Sowing densities: 15 kg ha^{-1} or 7.5 kg ha^{-1}. Tall fescue morphotype: continental turf-type (Cont.) or Mediterranean forage-type (Med.).

Trial	Sowing date	Maize harvest (aboveground)	Grass autumn biomass (aboveground)	Grass spring biomass (aboveground)	Soil nitrate concentration (0–0.9 m)	Grass root biomass (0–0.2 m)	Sowing methods and densities, grass morphotype
M14	30/04/2014	23/9/2014	25/11/2014	/	/	/	Drill 15 kg ha^{-1} Cont.
M15	28/04/2015	29/9/2015	09/12/2015	/	/	/	Drill 15 kg ha^{-1} Cont.
M16	13/05/2016	15/9/2016	29/11/2016	/	/	/	Drill 15 kg ha^{-1} Cont.
A16	08/05/2016	24/9/2016	10/11/2016	24/02/2017	/	/	Broad 15 kg ha^{-1} Cont.
M17	19/04/2017	19/9/2017	09/11/2017	30/03/2018	/	/	Broad 7.5 kg ha^{-1} Cont.
M18	09/05/2018	27/9/2018	17/12/2018	27/02/2019	17/12/2018	05/03/2019	Inter 15 kg ha^{-1} Cont. Broad 15 kg ha^{-1} Med.
M19	09/05/2019	Early: 09/09/2019 Late: 03/10/2019		17/03/2020	30/10/2020	18/03/2020	Broad 15 kg ha^{-1} Med.

in several plots after a summer storm in August. The whole field was harvested with the forage harvester.

Grass dry matter yield on the plots with intercropped grass was measured at the end of the autumn on all trials (except for M19) and in the period end of February to the end of March of the next spring on A16, M17, M18, and M19 (Table 3). At all harvest times, the grass was in the vegetative state of development. Per plot, an area of 1 m^2 was harvested by cutting the grass tillers manually just above the soil surface within a square frame. The harvested area was selected randomly, but wheel tracks from the harvest machinery were excluded from sampling. On plots where the grass was sown in three rows centrally between the maize rows, a length of 1.33 m was harvested, resulting in a representative sample of 1 m^2. The harvested grass biomass was rinsed with tap water to remove soil particles, dried for 16 h at 75 °C, and weighed to calculate matter content.

The dried spring harvested grass was analyzed for its carbon and nitrogen concentration in M18 and M19 using a CNS elemental analyser (Vario Macro Cube, Elementar, Germany). Soil residual nitrate concentration was measured in the 0–0.9-m soil layer before the start of the winter (Table 3) in M18 and M19. Using a gauge auger, four random spots were sampled per plot and the samples were bulked per plot. Soil samples were analyzed in a commercial lab (Soil Service Belgium, Heverlee, Belgium) for nitrate concentration. In brief, soil samples were extracted with KCl solution. The NO_3^- in the extract was reduced to NO_2^-, which was quantified colorimetrically.

Shortly after the spring grass harvest in M18 and M19, we sampled the root biomass (Table 3). Within the area harvested for grass biomass, a cubic container of 0.2 m × 0.2 m × 0.2 m was pushed into the ground and dug out to obtain a soil cube. This was done twice per plot. The upper 5 cm of the soil cube (containing the belowground stem pieces) was sliced off and analyzed separately from the rest of the soil cube. Belowground stem pieces and roots were washed from the soil on a sieve with a mesh size of 0.450 mm. Maize roots were easily discriminated from tall fescue roots: maize roots were decaying and less flexible than the grass roots and were discarded. Grass roots were dried and analyzed for N and C concentration using the procedure described above.

2.3 Data analysis

All data analyses were performed in R (R Core Team 2019) using the lme4 (Bates et al. 2015) and lmerTest (Kuznetsova et al. 2017) packages. Linear mixed models were fitted as *lmer*(*maize yield* ~ *grass yield* + (1|*block*)), to test the effect of the autumn grass biomass on maize yield in trials M14, M15, M16, A16, and M17. The data used to fit the models included the five treatments of trials M14, M15, M16 and the treatments “Broad 15 kg ha^{-1} Cont.” from A16, and M17. Finally, a model was fitted to all these data with factor *trial* as a categorical explanatory variable: *lmer*(*maize yield* ~ *grass yield* * *trial* + (1|*block*)); intercept and slope were estimated using Helmert contrasts.

The effects of the fixed factors *herbicide treatment* and *trial* and the random effect of *block* on the maize and grass yields of trials M14, M15, and M16 were estimated using *lmer*(*y* ~ *herbicide treatment* * *trial* + (1|*block*)).

In the trials focusing on sowing density, sowing method, and morphotype, we had maize yield data for two trials (A16 and M17) and five treatments (maize monocrop and four intercropping treatments), whereas for grass yield, we had data from three trials (A16, M17, and M18) and four treatments (four intercropping treatments). The effects of the fixed factors *intercropping treatment* and *trial* and the random effect of *block* on the maize and grass yields were estimated with *lmer*(*y* ~ *intercropping treatment* * *trial* + (1|*block*)). In the case of significant interactions, the data were split per trial to test the effects of the intercropping treatments *lmer*(*y* ~ *intercropping treatment* + (1|*block*)).

In M19, first, a two-way ANOVA was performed testing the effect of the fixed factors *maize varieties* (early and intermediate maturity) and *grass intercrop* (tall fescue intercrop and Italian ryegrass catch crop) on the maize yield in order to study the interaction effect between both factors with *lmer*(*y* ~ *maize variety* * *grass intercrop* + (1|*block*)). Next, the effects of the four combinations of *maize varieties* and *grass intercrop* were treated as one factor in *lmer*(*y* ~ *treatment* + (1|*block*)) to test the effects on maize yield, grass shoot and root biomass, C and N yields, and soil residual nitrate. We did so to allow comparison of specific combinations of maize variety and grass intercrop (early maize followed by a cover crop versus intermediate maize intercropped with tall fescue).

Based on a graphical visualization of the residuals, the data were found to meet normal distribution and homogeneity of variance. In case of significant treatment effects, means were compared using a post hoc Tukey test using the *glht* function of the *multcomp* package (Hothorn et al. 2008).

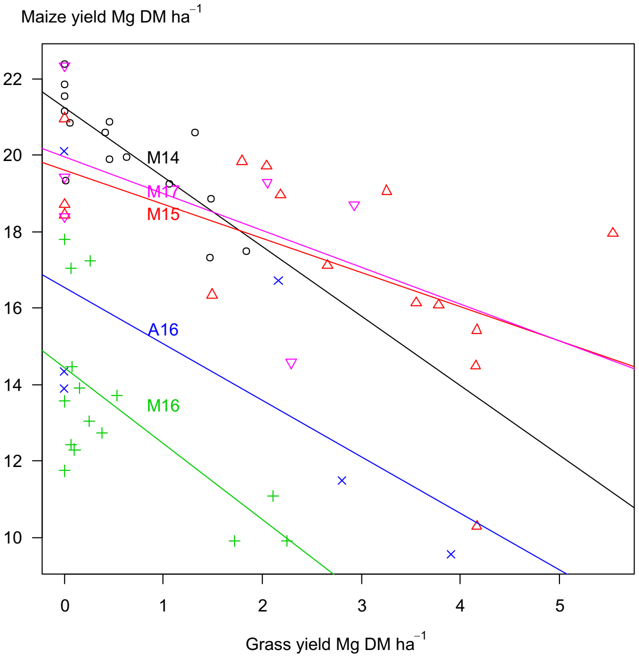

Fig. 2 Dry matter (DM) yield of maize intercropped with tall fescue as a function of the grass DM yield in autumn M14 (○): $y = 21241 - 1.82x$, $p < 0.001$, $R^2 = 0.69$; M15 (▲): $y = 19616 - 0.90x$, $p = 0.03$, $R^2 = 0.32$; M16 (+): $y = 14403 - 1.90x$, $p = 0.004$, $R^2 = 0.32$; M17 (▼): $y = 20082 - 1.07x$, $p = 0.12$, $R^2 = 0.32$; A16 (×): $y = 16108 - 1.19x$, $p = 0.02$, $R^2 = 0.97$.

3 Results

3.1 Maize yield loss due to grass

The effect of the intercropped grass on the maize yield in trials M14, M15, M16, A16, and M17 was trial dependent. The greatest effects were found in M14 and M16 where 1 kg DM ha^{-1} of continental turf-type tall fescue aboveground biomass, present in late autumn, caused a maize loss of, respectively, 1.8 and 1.9 kg DM ha^{-1} of maize yield. The smallest effect was found in M15 where 1 kg DM ha^{-1} of tall fescue caused a maize loss of 0.9 kg DM ha^{-1} (Fig. 2). In M17, the effect of grass presence, measured in autumn, on maize was not significant ($p = 0.12$). In the linear model fitted to the maize and grass yields over all trials, the presence of 1 kg DM ha^{-1} of continental turf-type tall fescue at the end of the autumn came along with a maize yield penalty of 1.4 kg DM ha^{-1} ($p < 0.001$; $R^2 = 0.81$).

3.2 Effects of herbicide treatments on maize and grass yields

Both maize and grass yields (measured at the end of the autumn) were significantly affected by *trial* ($p < 0.001$) and *herbicide treatment* ($p < 0.001$) in M14, M15, and M16; *trial* × *herbicide treatment* interaction was not significant ($p = 0.77$ for maize; $p = 0.11$ for grass). Maize yields were greatest in M14 (20.1 Mg ha^{-1}) and were significantly smaller in M15 (17.3 Mg ha^{-1}; $p < 0.001$) and M16 (13.4 Mg ha^{-1}; $p < 0.001$). Grass yields in M14 (0.8 Mg ha^{-1}) and M16 (0.7 Mg ha^{-1}) were significantly smaller ($p < 0.001$) than those measured in M15 (3.2 Mg ha^{-1}). In M14, M15, and M16, herbicide treatment C, based on herbicides controlling broadleaf weeds, allowed the grass intercrop to develop too well and resulted in significant maize yield reductions of 18 %, 27 %, and 28 % in M14, M15, and M16, respectively, compared to the maize monocrop (Fig. 3). In treatment D, on the other hand, the presence of nicosulfuron killed almost all the grass in M14 and M16, resulting in similar maize yields as in the maize monocrop.

3.3 Effects of tall fescue morphotype and sowing method on grass and maize yields

The effect of *intercropping treatment* on the maize yield was not significant ($p = 0.06$), meaning that neither sowing density nor sowing method and morphotype of the intercropped tall fescue affected maize yield significantly. There was a significant effect of *trial* ($p < 0.001$) on maize yield: yields in A16 (14.5 Mg ha^{-1}) were lower compared to M17 (17.9 Mg ha^{-1}) (Table 4). There was no *intercropping treatment* × *trial* interaction for maize yield ($p = 0.13$).

There was a significant effect of *intercropping treatment* ($p = 0.006$) on the autumn grass yield; the *intercropping treatment* × *trial* interaction ($p = 0.35$) was not significant. For

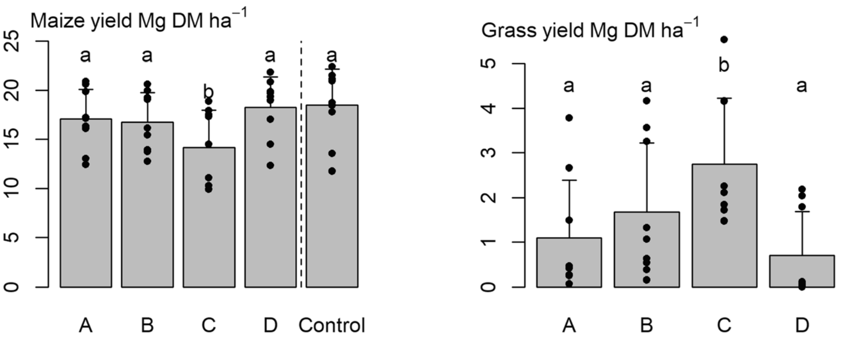

Fig. 3 Dry matter yields of maize (left) and tall fescue (right) when intercropped, in function of herbicide treatments A–D as indicated in Table 2 averaged over trials M14, M15, and M16. The treatment "Control" corresponds to monocropped maize receiving herbicide treatment A. Letters above the bars indicate significant differences between the herbicide treatments. Error bars denote standard deviations.

spring grass yield, however, a significant *intercropping treatment* × *trial* interaction ($p = 0.0018$) was found; hence, the effect of *intercropping treatment* was tested per trial. In order to compare the autumn versus spring biomass, we analyzed the data of the autumn grass biomass in the same way (Table 4). In M17, the autumn grass biomass of "Broad 7.5 kg ha^{-1} Cont.," was just significantly ($p = 0.042$) lower compared to the treatments sown at 15 kg ha^{-1}, whereas in M18, the treatments "Broad 7.5 kg ha^{-1} Cont." and "Inter 15 kg ha^{-1} Cont." had a significantly ($p = 0.013$) lower yield compared to "Broad 15 kg ha^{-1} Med." (Table 4). Autumn biomass of "Broad 15 kg ha^{-1} Cont." and "Broad 15 kg ha^{-1} Med." were not significantly different, but the greater winter growth of the Mediterranean forage-type compared to the continental turf-type resulted in a significantly greater spring grass biomass for the former in M17 ($p = 0.004$) and M18 ($p < 0.001$). Remarkably, the grass biomass decreased over winter for all (but one) treatments in A16 because of the very wet conditions on the experimental field, resulting in a decay of the standing grass biomass over winter.

3.4 Carbon yield by tall fescue

The greater spring shoot biomass yield of the Mediterranean forage-type (4.7 Mg ha^{-1}) compared to the continental turf-type (2.5 Mg ha^{-1}) in M18 resulted in a significantly greater ($p < 0.001$) total carbon yield (Table 5). This difference was mainly explained by the significantly higher shoot carbon yield ($p = 0.004$) and to a lesser extent to differences in root carbon below 5-cm depth (Table 5).

In M19, the shoot biomass yield and the carbon yield of shoot and root for the Mediterranean type fescue were lower compared to M18, but averaged over both trials, the

Table 4 Maize and grass dry matter yields measured in trials A16, M17, and M18, either in maize monocrops or intercropped with tall fescue. Intercropping treatments differing in the sowing method: broadcast (Broad) versus interrow-sown (Inter); the sowing density: 15 kg ha^{-1} versus 7.5 kg ha^{-1}; or the tall fescue morphotype: continental turf-type (Cont.) versus Mediterranean forage-type (Med.). ANOVA compared four intercropping treatments for grass yield. Within each column, means followed by the same letter are not significantly different ($\alpha = 0.05$, Tukey test).

			Maize yield (kg ha^{-1})			Autumn grass yield (kg ha^{-1})			Spring grass yield (kg ha^{-1})		
			A16	M17	M18	A16	M17	M18	A16	M17	M18
Maize intercropped with grass											
Broad	15 kg ha^{-1}	Cont.	12593	17522	/	2955	2424_a	2325_{ab}	2745	3125_b	2472_b
Broad	7.5 kg ha^{-1}	Cont.	11978	17152	/	2135	1289_b	2011_b	2492	2012_b	2203_b
Inter	15 kg ha^{-1}	Cont.	17143	16958	/	1729	1656_a	2011_b	1570	2694_b	1864_b
Broad	15 kg ha^{-1}	Med.	14648	17708	/	2411	2324_a	3448_a	2111	4701_a	4692_a
Maize monocrop			16119	20050	/						
p-value						0.35	0.042	0.013	0.20	0.0038	0.0003
Average intercropping treatments			14090	17335	/	2307	1923	2449	2230	3133	2808
Average all treatments			14496	17878							

Table 5 Spring grass biomass, carbon (C) and nitrogen (N) yields, and soil residual nitrate reduction compared to monocropped maize in the 0 to 0.9 m soil profile for continental turf-type tall fescue (Cont.) versus Mediterranean forage-type tall fescue (Med.) broadcast sown at 15 kg ha^{-1}in M18 and for Med. in M19.

			M18			M19
			Cont.	Med.	*p*-value	Med.
Biomass yield	Shoot	kg DM ha^{-1}	2472	4692	0.0045	3810
	Root 0–5 cm	kg DM ha^{-1}	5183	4833	0.49	3488
	Root 5–20 cm	kg DM ha^{-1}	1508	2283	0.24	2288
	Total	kg DM ha^{-1}	9164	11809	0.014	9589
C yield	Shoot	kg C ha^{-1}	972	1931	0.00397	1596
	Root 0–5 cm	kg C ha^{-1}	1638	1696	0.79	1110
	Root 5–20 cm	kg C ha^{-1}	484	887	0.046	811
	Total	kg C ha^{-1}	3094	4515	<0.001	3517
N yield	Shoot	kg N ha^{-1}	64	96	0.054	56
	Root 0–5 cm	kg N ha^{-1}	106	74	0.0092	31
	Root 5–20 cm	kg N ha^{-1}	23	25	0.805	26
	Total	kg N ha^{-1}	193	195	0.941	113
C/N ratio	Total	–	16	23		31
Soil nitrate reduction		kg NO_3-N ha^{-1}	129	128	0.87	43

distributions of the carbon in shoot, root 0–5 cm, and root 5–20 cm fractions were 43 %, 36 %, and 21 %, respectively. Hence, in early spring, for every kg carbon measured in the tall fescue shoot, approximately 1.3 kg carbon was found belowground.

3.5 Grass nitrogen uptake and reduction of soil nitrate

Despite the higher shoot biomass yield of the Mediterranean forage-type compared to the continental turf-type tall fescue in M18, the total N yields were almost equal: 193 versus 195 kg N ha^{-1} ($p = 0.941$) (Table 5).

In M18, soil residual nitrate was decreased from 150 kg NO_3-N ha^{-1} after the maize monocrop to 21 and 22 kg NO_3-N ha^{-1} after the maize intercropped with continental and Mediterranean tall fescue ($p = 0.0396$; results not shown). The resulting soil nitrate reductions relative to the maize monocrop, 129 and 128 kg NO_3-N ha^{-1} for continental and Mediterranean tall fescue, respectively, were not different ($p = 0.87$) (Table 5). In M19, the N uptake of the Mediterranean tall fescue was 113 kg N ha^{-1}. The soil residual nitrate in the maize monocrop was 90 kg NO_3-N ha^{-1} and 47 kg NO_3-N ha^{-1} after the intercropped tall fescue ($p = 0.254$; results not shown), resulting in a reduction of 43 kg NO_3-N ha^{-1} (Table 5).

Shoot, root (0–5 cm), and root (0–20 cm) N concentrations were, respectively, 2.5 %, 2.1 %, and 1.2 % for continental turf-type tall fescue and 2.0 %, 1.6 %, and 1.2 % for Mediterranean tall fescue in M18 and 1.5 %, 0.8 %, and 1.2 % in M19. The proportion of the total plant N captured in the root biomass ranged from 0.67 to 0.51.

3.6 Intercropped grass versus catch crop grass sown after maize harvest

In M19, a significant *maize variety* × *grass* interaction ($p = 0.00182$) was found. The effect of the intercropped tall fescue was greater on the early maize variety (−15 % yield) compared to the intermediate maize variety (+2 % yield) (Table 6). Within each maize maturity group (early or intermediate), the spring shoot biomass yield of the Mediterranean tall fescue was significantly greater compared to the Italian ryegrass cover crops (6.3 Mg ha^{-1} versus 3.8 Mg ha^{-1} for the early maize harvest; 3.8 Mg ha^{-1} versus 1.5 Mg ha^{-1} for the intermediate maize harvest). These differences in biomass yields were translated in significantly different N yields but not in soil residual nitrate reductions (Table 6).

M19 allows to compare two alternatives to reduce nitrate leaching in forage maize production: an early maize variety grown as a monocrop, harvested early September and followed by a cover crop of Italian ryegrass (early maize, Monocrop Lm in Table 6) versus an intermediate maize variety, intercropped with Mediterranean tall fescue, harvested early October (intermediate maize, Intercrop Fa in Table 6). Yields of the monocropped early maize variety (22.7 Mg ha^{-1}) and the intermediate maize intercropped with tall fescue (22.5 Mg ha^{-1}) were similar as well as the corresponding spring yields of grass biomass of the Italian ryegrass cover crop (3.8 Mg ha^{-1}) and the intercropped Mediterranean tall fescue (3.8 Mg

Table 6 Maize yield, spring grass shoot biomass, carbon (C) and nitrogen (N) yields, and reduction of soil residual nitrate in the 0 to 0.9-cm soil profile for an early maize variety harvested early September and an intermediate maize variety harvested early October in trial M19. Both either intercropped with Mediterranean forage-type tall fescue (Intercrop Fa) or followed by an Italian ryegrass catch crop (Monocrop Lm).

		Unit	Early maize harvest		Intermediate maize harvest		*p*-value
			Intercrop Fa	Monocrop Lm	Intercrop Fa	Monocrop Lm	
Maize yield		kg DM ha^{-1}	19211_b	22656_a	22462_a	21927_a	<0.001
Grass							
Shoot biomass yield		kg DM ha^{-1}	6320_a	3769_b	3810_b	1541_c	<0.001
C yield	Shoot	kg C ha^{-1}	2633_a	1574_b	1596_b	646_c	<0.001
	Root 0–5 cm	kg C ha^{-1}	1386	1310	1110	536	0.073
	Root 5–20 cm	kg C ha^{-1}	876	569	811	546	0.073
	Total	kg C ha^{-1}	4895_a	3453_b	3517_b	1728_c	<0.001
N yield	Shoot	kg N ha^{-1}	110_a	64_b	56_b	19_c	0.004
	Root 0–5 cm	kg N ha^{-1}	41_a	39_a	31_{ab}	15_b	0.032
	Root 5–20 cm	kg N ha^{-1}	34	18	26	22	0.302
	Total	kg N ha^{-1}	184_a	121_b	113_{bc}	57_c	0.009
Soil nitrate reduction		kg NO_3-N ha^{-1}	68	74	43	42	0.856

ha^{-1}). The total carbon and nitrogen yields for tall fescue intercropped in the intermediate maize (3517 kg C ha^{-1} and 113 kg N ha^{-1}) were not significantly different compared to those of the Italian ryegrass following the early maize (3453 kg C ha^{-1} and 121 kg N ha^{-1}). Neither were the soil residual nitrate contents measured in plots with Italian ryegrass after early maize (51 kg NO_3-N ha^{-1}) and Mediterranean tall fescue intercropped in intermediate maize (47 kg NO_3-N ha^{-1}). The lower soil residual nitrate in the monocropped intermediate maize (90 kg NO_3-N ha^{-1}) compared to the monocropped early maize (125 kg NO_3-N ha^{-1}) resulted in a non-significantly, but apparently higher soil residual nitrate reduction in Italian ryegrass (125 − 51 = 74 kg NO_3-N ha^{-1}) compared to the intercropped tall fescue (90 − 47 = 43 kg NO_3-N ha^{-1}).

4 Discussion

4.1 Competition between maize and intercropped grass

The results showed that the presence of the intercropped grass resulted in considerable maize yield losses (up to 28 %). The present study was not designed to determine whether water or nitrogen was the limiting factor for the yield of the intercropped maize. Manevski et al. (2015) found that N was the limiting factor for maize yield in a trial with maize intercropped with red fescue (*Festuca rubra* L.) on sandy soils in Denmark. They found that intercropped maize yielded up to 19 % less compared to a maize monocrop at the prescribed standard N rate for maize (190–250 kg N ha^{-1} according to year), whereas this difference disappeared almost when the intercropped maize received an additional 60 kg N ha^{-1} from mineral N fertilizer. Also Wachendorf et al. (2006) found that the negative yield effect of an understory of perennial ryegrass, sown in the 3–4-leaf stage of the maize, decreased with increasing rates of mineral N fertilizer. However, from an environmental point of view, increasing N fertilization to decrease competition between maize and intercropped grass is not a good option.

The relation of − 1.4 kg ha^{-1} of maize DM for every kg ha^{-1} of aboveground grass DM present in autumn is valid just for the turf-type tall fescue varieties tested, averaged over several years. Unfortunately, we did not have enough data to make the same exercise for the Mediterranean tall fescue variety tested.

The yield cost should be balanced against the benefits delivered by the intercropped grass: the N released by the plowed down grass cover crop in the following crop and the long-term beneficial effect of the cover crop biomass on the soil fertility (Thorup-Kristensen et al. 2003).

4.2 Options to influence the grass-maize competition

The results illustrate well that in maize with intercropped grass, the herbicide treatments should be balanced with care: they should not only eliminate competition from weeds but also suppress the development of the intercropped grass without wiping it out. If the suppression of the intercropped grass or weeds is absent or too weak as in treatment C, the competition from grass resulted in maize yield reductions up to 28 %.

Herbicides with a good action against grasses can kill the intercropped grass. Consequentially, in fields where a high competition of grass weeds or panicoid grasses (*Echinochloa* sp., *Digitaria* sp., *Panicum* sp.) is expected, for example, fields with a history of maize monoculture (Claerhout et al. 2015), finding a treatment that meets both requirements is difficult. As herbicide activity depends on soil and climatic conditions (Zimdahl 2007), the herbicide schemes used in this study are only relevant for our local conditions. Herbicide mixtures should be adapted to local growing conditions and regulations.

The important season effect on the intercropped grass yield in M14, M15, and M16 cannot be explained by the growing conditions after the maize harvest only. Indeed, the temperature sum (base 5 °C) in the period between the maize harvest and the harvest of the aboveground grass biomass in the autumn varied from 572 °C·d in 2014, 505 °C·d in 2015 to 450 °C·d in 2016. Yet we monitored the highest grass biomass production in M15 (2015) and the lowest in M16 (2016), the difference between these years not being in proportion to the temperature sum. This indicates that among-year differences were also influenced by other factors that occurred earlier in the growing season including the grass density and the weather conditions after the herbicide applications that are known to influence herbicide action and the vigor of the grass intercrop.

In the present study, neither decreasing the grass sowing density to 7.5 kg ha^{-1} nor limiting the distribution of the grass to the maize interrow area offered perspectives to decrease the competition between the grass and the maize compared to the continental turf-type broadcast sown at 15 kg ha^{-1}. The reduced sowing density resulted in a very open, heterogeneous sward in 2017, jeopardizing the cover crop functions (nitrate uptake, erosion control, etc.) of the sward. The distance of 0.225 m between the maize row and the closest grass row in the interrow proved to be too small to reduce grass-maize competition significantly, which eventually is not surprising given the deep and long roots of tall fescue (Cougnon et al. 2017). Sowing the grass just in one row in the middle of the maize interrow could have resulted in a greater effect, but this option was not tested in the present study because we expected an insufficient cover crop function with just one grass row every 0.75 m.

The use of Mediterranean instead of continental tall fescue offered limited perspectives to decrease the competition. In Mediterranean tall fescue, summer dormancy only occurs in plants having previously experienced winter conditions and flowering, whereas in spring-sown Mediterranean tall fescue, severe summer drought can induce a partial summer dormancy (Norton et al. 2006). Although the summer of 2018 was exceptionally dry, with only 107 mm of rain in the period June–August compared to a long-term average of 229 mm for this period, the expected (partial) summer dormancy of Mediterranean tall fescue probably did not occur. The typical autumn and winter growth on the other hand was clearly present in our trials, resulting in greater spring biomass yields of the Mediterranean morphotype compared to the continental turf-type.

4.3 Grass biomass, carbon and nitrogen yields, and reduction of soil residual nitrate

More than half of the carbon measured in the spring grass biomass of the intercropped tall fescue was found belowground. It is difficult to compare these results with those from other studies. In the studies of Wachendorf et al. (2006) and Manevski et al. (2015), dealing with undersown or intercropped grass in maize, the root biomass was not determined or specified. The values for root carbon yields reported in studies with cover crops sown after the maize harvest (for example, 610 kg root carbon ha^{-1} in Austin et al. (2017)) are much lower than those reported here, probably due to the shorter growing period of cover crops compared to our intercropped grass. Root biomass is known to contribute disproportionally more to soil organic matter build-up than shoot biomass (Rasse et al. 2005). Austin et al. (2017) found that, compared to shoot carbon, the belowground carbon (roots + root exudates) of a winter rye cover crop was three times more likely to be stored as soil organic carbon. Poeplau et al. (2015) found a humification coefficient (h), the proportion of the organic matter input that is converted to humus, of 0.33 for perennial ryegrass cover crops (shoot + root). Hypothesizing that tall fescue has a similar humification coefficient, the 3000–4500 kg C ha^{-1} from intercropped tall fescue would result in 990–1485 kg soil organic carbon (SOC) ha^{-1}. Whether this is sufficient to stabilize SOC under forage maize remains to be studied. However, yearly SOC mineralization can be typically around 1100 kg SOC ha^{-1} on arable land in the study region (1.1–1.4 % SOC) (Hofman and Van Ruymbeke 1980) so in many cases the intercropped tall fescue would allow to compensate SOC mineralization and hence stop the decline of SOC associated with forage maize cultivation.

The proportion of the total plant N captured in the intercropped tall fescue root biomass in M18 and M19 ranged from 0.67 to 0.51. These values are higher than those found in studies with rye catch crops sown after the maize harvest, where the proportion of total N captured in roots was between 0.33 (Van Dam and Leffelaar 1998), and below 0.50 for Italian ryegrass (Komainda et al. 2016). The higher proportions in the present study are not surprising as the intercropped grass was almost 1 year old when sampled in spring and appeared as a mature grass sward, rather than a cover crop.

The high soil residual nitrate measured in the maize monocrop in M18 can be explained by the very dry conditions in June–July 2018 limiting the growth and the N uptake of the maize. The measured value was in line with the average soil residual nitrate of 107 kg NO_3-N ha^{-1} after forage maize measured in 2018 in Flanders (VLM 2020). Both types of intercropped tall fescue significantly reduced the soil residual nitrate in M18. The superior winter growth of the Mediterranean morphotype, however, did not lead to a superior reduction in soil residual nitrate compared to the continental turf-type.

The reductions in soil nitrate content for intercropped Mediterranean tall fescue and Italian ryegrass sown after maize harvest were similar in M19, both after the harvest of the early and the intermediate maize. The weather in the autumn-winter of 2019–2020 may explain this unexpected outcome. Both autumn 2019 (September–November) and winter (December–February) were very mild with average temperatures of 11.3 °C (versus 10.9 °C normally) and 6.3 °C (versus 3.6 °C normally), respectively, which favored the rapid development and N uptake of the Italian ryegrass. The impact of the temperature on the N uptake in the period after sowing can be illustrated by calculating aboveground and belowground N (AGN and BGN in kg N ha^{-1}) of catch crop of Italian ryegrass sown after maize using the regression equations developed by Komainda et al. (2016):

$$AGN = e^{(-0.187+0.0071\times Tsum)}$$

$$BGN = e^{(-3.59+0.0148\times Tsum)}$$

Over a period from sowing until harvest, the Italian ryegrass in M19 received a temperature sum (Tsum; base 5 °C) of 620 °C·d and 396.3 °C·d for the mid-September- and early-October-sown Italian ryegrass, respectively. According to these models, this would result in estimated N yields in the grass of 335 kg N ha^{-1} (68 kg N ha^{-1} AGN + 267 kg N ha^{-1} BGN) and 23.5 (13.8 kg N ha^{-1} AGN + 9.7 kg N ha^{-1} BGN), respectively. The unrealistically high BGN value found for the mid-September-sown Italian ryegrass is due to extrapolation: Tsum data used to build the models were indeed limited to the range 100–500 °C·d (Komainda et al. 2016). Performing the same calculation using the temperatures averaged over the last 10 years (2010–2019), the Tsums for the growing period are 515.3 °C·d and 312.9 °C·d for the mid-September- and early-October-sown Italian ryegrass resulting in estimated grass N yields of 88.8 kg N ha^{-1} (32.2 kg N ha^{-1} AGN + 56.6 kg N ha^{-1} BGN) and 10.5 (7.6 kg N ha^{-1} AGN + 2.8 kg N ha^{-1} BGN), respectively. So the mild temperatures in autumn-winter 2019–2020 resulted in higher Italian ryegrass N yields than would have been the expected in an average autumn-winter and it is thus likely that the potential to reduce soil residual nitrate of Italian ryegrass would have been smaller in an average autumn-winter.

Another argument why a higher reduction of soil residual nitrate of intercropped tall fescue compared to Italian ryegrass cover crops was expected comes from root architecture. Rooting depth of catch crops is of greater importance than rooting density to reduce soil residual nitrate (Thorup-Kristensen 2001). After sowing, the root depth penetration of Italian ryegrass was found to be 1.1 mm (°C·d)$^{-1}$ (Thorup-Kristensen 2001). Given the average Tsums calculated above, roots of mid-September-sown Italian ryegrass are expected to grow not deeper than 0.6 m. As the rooting depth of tall fescue reaches up to 0.9 m in the study area (Cougnon et al. 2017), the intercropped tall fescue is expected to have an advantage compared to Italian ryegrass sown after maize harvest to take up soil residual nitrate, especially in the first weeks after sowing of Italian ryegrass.

Both in M18 and in M19, the N yield of the intercropped tall fescue exceeded the reduction in soil nitrate at the end of the growing season. This is an indication for competition for N: the intercropped grass takes up N that presumably would have been taken up by the maize in the absence of the intercropped tall fescue.

The yield loss associated with intercropping compared to monocrop maize should be nuanced. Intercropping maize, from an intermediate maize variety, with tall fescue allows to obtain the same N and C yields and soil residuals nitrate reduction as with a timely installed Italian ryegrass cover crop. To obtain a timely installed Italian ryegrass crop, the use of early maize varieties is necessary. The generally higher yield potential of intermediate maize varieties compared to early varieties could thus compensate for the maize yield loss caused by the intercropped tall fescue competition. Against this expectation, in the present trial, the monocrop yield of the early maize variety was not lower than that of the intermediate variety.

The maize yield of the intermediate-maturing variety was not affected by grass species, whereas the early-maturing variety suffered yield loss when intercropped with tall fescue. Similar interaction between maize varieties and competing weeds has been shown (Marín and Weiner 2014). This finding suggests that specific combinations of maize and tall fescue varieties can be found in which competition is further decreased.

5 Conclusion

Intercropping maize with continental turf-type tall fescue at a density of 15 kg ha^{-1} resulted on average in a yield loss of 1.4 kg DM ha^{-1}of maize for every kg DM ha^{-1} aboveground grass biomass measured in late autumn.

For the first time, this study quantified different methods to regulate competition between forage maize and intercropped tall fescue. Chemical weed control proved to be a powerful lever for adjusting the grass-maize competition. However, it is not obvious to predict the precise effects of a herbicide treatment on the developing grass sward due to the influence of the post-treatment weather on the herbicide activity. Decreasing the grass sowing density from 15 to 7.5 kg ha^{-1} or sowing the grass in the maize interrow area, 0.225 m away from the maize rows rather than broadcast sowing, offered limited perspectives to decrease the grass-maize competition in our study.

Despite the absence of summer dormancy in the intercropped Mediterranean forage-type tall fescue, this morphotype had a pronounced autumn and winter growth resulting in a greater biomass production compared to the turf-type tall fescue. Spring carbon total yields were at least 3.1 Mg C ha^{-1}. This superior winter growth of the Mediterranean morphotype, however, did not lead to a superior reduction in soil residual nitrate compared to the continental turf-type as both types were able to reduce soil mineral nitrate with values up to 128 kg NO_3-N ha^{-1}. The early maize variety suffered a yield loss of − 15% when intercropped with tall fescue compared with an Italian ryegrass catch crop, whereas this was not found for the intermediate maize variety. Within both maize maturity groups, the intercropped tall fescue was superior in biomass production compared to the Italian ryegrass cover crop, but this did not lead to greater reduction in soil residual nitrate.

Finally, our results indicate that a maize monocrop harvested early September followed by an Italian ryegrass catch crop can be similar in terms of maize yield, nitrate leaching reduction, and grass organic matter production to maize intercropped with Mediterranean tall fescue harvested early October.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable for the present study.

Consent to participate Not applicable for the present study.

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