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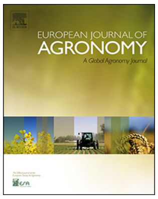

Sensitivity of silage-maize to climate change in Denmark: A productivity analysis using impact response surface

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ABSTRACT

The sensitivity of silage maize to changing climate in Denmark under varying Nitrogen (N) and undersown catch crop (CC) treatments was investigated using a process-based, soil-plant-atmosphere model; Farm Assesment Tool (FASSET), and the impact response surfaces (IRS). The baseline period consisted of an experiment over a 3-year time period from 2009 to 2011 that was carried out in mid Jutland, Denmark (56°5′N, 9°56′E 38 m asl). The results indicated that an increase from the average annual temperature (≈6.5 °C) of up to 1.5 °C is beneficial for maize yield. At approximately 8 °C annual average temperature and above, the yield dropped sharply, and any positive impact of varying N treatments and CC was diminished. The maize yield was not as sensitive to precipitation as it was to temperature. The undersown grass in silage maize was not found to be a viable option in relation to warmer climate for all of its benefits were widely overshadowed by the excessive NO_3^- leaching risk. This study suggested that the warming of the climate along with the projected increase in precipitation in Denmark in the future will greatly challenge the management of N in maize cropping systems. Under changing climate, increasing crop N uptake efficiency by both maize and CC should be targeted as priority. Root growth in this context is an essential feature for the N uptake efficiency. Further research on potential adaptation of different deep-rooted species in the warmer climate that might be suitable as undersown CC is needed.

1. Introduction

The changes in climatic conditions are altering the crop cultivation practices in many areas. In Europe, an increase of about 0.9 °C in temperature has been experienced since the early 1900 s. The warming rate was between 0.13 and 0.24 °C per decade for 20-year periods since 1976, and the ten warmest years throughout the recording period have occurred since 2000 (Parry et al., 2007). In Northern Europe specifically, seasonal variations in temperature and precipitation patterns now allow grain maize production in Lithuania and Southern Sweden, and forage maize in Denmark, Estonia, Latvia and Norway (FAO, 2015). The shifting in maize cultivation areas towards the north are projected to continue into the future (Fronzek and Carter, 2007). Given the expanding cultivation areas and insufficient knowledge on maize production in Northern Europe, further research regarding the maize response to changing climate in Northern Europe is needed. Specifically, the response of crop growth, and the differential response between mono-crop and catch-crop systems, or varying levels of N fertilization effects are much sought for.

While maize has high N uptake potential, it is associated with highly fluctuating levels of soil mineral N after harvest (Hansen and Eriksen, 2016). N processes are inevitably affected by the increased temperature, and increased or decreased soil moisture. Christensen and Christensen (2007) suggested that the annual mean temperature in Scandinavia will increase by as much as 4.16 °C, and the precipitation by 9% by 2080. Under these conditions, the mineralization rate of N in crop residues and soil organic matter was expected to increase in Denmark (Olesen et al., 2004), potentially leading to significant amount of N losses through leaching especially in sandy soils (Askegaard et al., 2011). In maize cultivation, the amount and timing of fertilizer N applications, grass as an under sown cover crop, and N dynamics are therefore receiving increasing attention. While the studies highlight the complexity of intercropping and its effects on soil N dynamics even at a local scale (Hansen et al., 2000; Buchter et al., 2003; Hansen and Eriksen, 2009; Manevski et al., 2015; Hansen and Eriksen, 2016), the complexity further increases when accounting for the potential effects of climate change (Patil et al., 2010).

With a goal of analyzing the sensitivity of maize to wide range changes in temperature and precipitation, we present a detailed maize crop response analysis to climate change, in which the effects of

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different fertilization strategies and CC were taken into account. The current study was designed to show a spectrum of simulated responses to climate change of one year (2010) of an experiment that was carried out between 2009 and 2011. This was achieved using the IRS approach. IRS allows presenting the response of a state variable to two or more independent variables. The main principle behind the IRS is to help optimize the use of resources by designing experiments (Box and Wilson, 1951). Because it is used determining the optimal value of the independent variables that produces a maximum or minimum response, IRS can be adopted to investigate the response of the crops to climate change. As such, this approach had been introduced in the investigation of crop yield response (e.g. Pirttioja et al., 2015), crop production potential under climate change (Van Minnen et al., 2000), and the optimization of resource use in crop production (Koocheki et al., 2014). In this study, we investigated the sensitivity of the silage maize to climate change in Denmark under varying N fertilization and CC treatments.

2. Materials and methods

2.1. Study area

The experiment site is located in Foulum, mid Jutland, Denmark (56°5′N, 9°56′E 38 m asl), where the landscape is flat and the soil is of sandy loam glacial tills from the Weichsel glaciation (Breuning-Madsen and Jensen, 1996). The soil is free draining and consists of 8% clay, 11% silt and 79% sand at the top 25 cm level with bulk density of 1.54, and organic carbon content of 2.4%.

The climate in the study area is temperate with winter (December - January) mean temperature around 0 °C and summer (June-August) mean of 17 °C. The average annual precipitation is approximately 715 mm. The annual potential evapotranspiration (PET) is approximately 550 mm, and the actual is approximately 380 mm. PET exceeds precipitation in spring and early summer, leading to depletion of soil water. In late autumn, winter and early spring, 150–400 mm water leaches through the soil. Due to precipitation surplus in late autumn, soil water reserves are replenished (Cappelen, 2012).

2.2. Experimental design and, treatments

The experiments were carried out in a three-year period from 2009 to 2011 on randomized split-split plots (9 × 12 m) with three replicates. The main plot treatment was the 10-year cropping history (1999–2008) of either continuous silage maize or grass-clover mixture intermittently undersown to spring barley. For the current study, we used the cropping system that consisted of continuous silage maize (with spring rape sown only in 2004). The experiments had two subplot treatments that were used in this study. The first was the N fertilization rates at prescribed by standard rate for maize (Plantedirektoratet, 2013) at approximately 160 kg N ha^{-1}, 50% below, and 50% above recommended levels. From here onward the N rates are denoted as N, 0.5 N, and 1.5 N. For N treatments, a combination of mineral and organic forms was applied (Table 1). The N was applied in April each year with two to five days of difference between the application of organic and mineral form. The second subplot treatment was the use of CC. Maize was grown both as monoculture and intercropped with red fescue (*Festuca rubra*) sown simultaneously with maize, and Italian ryegrass (*Lolium multiforum*) sown in June. During the experiments, the maize was sown in late April following a plow, and harvested in mid-October. The CC were kept on the field until the next spring plow. In the experimental plots, the pests and diseases were carefully controlled.

Table 1
Annual amount and type of N input during the 10-year cropping history and the actual experimental period between 2009 and 2011.

10-year cropping history	Actual experiments (2009 – 2011)						
Mineral/Organic N ratio	Year	Mineral (kg N ha^{-1})			Organic (kg N ha^{-1})		
		0.5 N	1 N	1.5 N	0.5 N	1 N	1.5 N
142/32	2009	20	20	80	86	184	184
	2010	20	20	80	85	170	170
	2011	40	40	100	106	212	212

2.3. The FASSET model and calibration

FASSET is a whole farm model that includes the detailed simulation of crop growth dry matter production and N content of vegetative, storage and root organs on a daily basis in response to soil, climate, crop management, water and N inputs (Berntsen et al., 2004). The baseline simulations were carried out using daily meteorological (max and min air temperatures, solar radiation, and precipitation), soil (bulk density, soil water retention, saturated hydraulic conductivity, clay, C and N content), and management data (sowing, harvesting, tillage and fertilization). While maize was sampled four times, the rest of the crops were sampled three times during the growing season and at harvest covering the period 2009 - 2011. Manevski et al. (2015) contained the detailed description on data collection and sampling. Daily climate data including maximum and minimum temperatures, precipitation, solar irradiance and reference evapotranspiration for the baseline period were obtained from the weather station of Danish Meteorological Institute located at the study site.

FASSET (version 2.5) is calibrated using a step-by-step method. First, we have run the model with default parameter values. The calibration had started with fitting the simulated soil water content to the observed value. Concurrently, the crop phenology, crop biomass, and N contents were fitted. Lastly, soil mineral N was fitted to the measured values. For the optimization of the FASSET parameters, the differential evolution algorithm for global optimization was used in R 2.1.4.1 via 'DEoptim' package (Mullen et al., 2011). In summary, several parameters were first selected to assess their sensitivity. These parameters were then tested using the sensitivity package in R 2.1.4.1 (Gilles et al., 2016). The parameters that were determined to be affecting the phenological development of maize and the CC, the biomass and N content of maize, as well as the biomass of CC, and finally the soil mineral N content were; the sum of temperatures in each crop phase, maximum radiation use efficiency, the fraction of dry-matter that present at initiation of grain filling that is translocated to grain, the fraction of net production after anthesis that goes into grain, maximum ratio between leaf area index and the dry matter of the vegetative above-ground biomass, maximum ratio between leaf area index and the nitrogen of the vegetative above-ground biomass, and the minimum soil NO_3^-. The parameters were optimized one at a time within 95% of above and below the default values. The R software then performed number of iterations until the best value for a parameter (a value that led minimum deviation of the model outputs from the observed values) was generated (Table 2). For the optimization of the phenological parameters, and the initial soil water content, no specific algorithm was used. The sum of temperatures of the each crop phase was manually adjusted to fit the simulations to the observed phenological stages. The parameter that affect the soil water content most (initial soil water content) was also manually adjusted to fit the simulated soil water content to the observed.

Because FASSET has been validated numerously using independent datasets and widely utilized in relation to the current study site (e.g. Doltra et al., 2011; Rotter et al., 2012; Doltra et al., 2015), an additional validation procedure was omitted in this study. To assess the models' simulation performance however, different statistical indexes were used. Normalized root mean square prediction error ($RMSPE_n$) was presented reflecting the accuracy of the simulated values. The closer the $RMSPE_n$ to zero, the more accurate the simulated values are (Tedeschi, 2006). $RMSPE_n$ was determined as: