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Variables influencing yield-scaled Global Warming Potential and yield of winter wheat production

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ABSTRACT

The main goal of this study was to determine the major drivers of variation for the yield-scaled Global Warming Potential (GWP) and yield of winter wheat in Poland focusing on environmental, genetic and management variables. The yield-scaled GWP is the GWP calculated per grain unit expressed in kg CO_2 equivalent kg^{-1} yield. The analysis was performed using multivariate statistical methods: CART (classification and regression tree) and RF (random forest). This is the first study in Poland to focus on variables besides those used in GWP calculations and those influencing the yield-scaled GWP variability of winter wheat production. Identification of these variables contributes to the creation of more environmentally friendly wheat cropping systems. In this study, regression-tree based analysis revealed that soil quality and water availability during crucial stages of plant growth are the most influential input variables of the yield-scaled GWP and yield variability in winter wheat production. Not surprisingly, environmentally favorable conditions for wheat growth contribute to its high yields yet require less intensified agronomic management. The strong influence of water availability in June and July, at the end of plant growth, applies to the undesirable effect of excess water leading to plant diseases which result in lower yield. N fertilizer has a strong effect on GWP of winter wheat production. However, this study also shows that nitrogen is not one of the most influential variables of wheat yield variability. Thus, increasing its average use in Polish environmental conditions from 107.3 kg ha^{-1} to 147.3 kg ha^{-1} might not increase yield sufficiently for its use to be justified. More important variables of yield variability were the use of fungicides and growth regulators, which are applied at much smaller rates (1.7 and 0.8 kg ha^{-1}, respectively) than N fertilizer and positively influence efficient winter wheat production.

1. Introduction

Cereal-based cropping systems contribute to different greenhouse gas (GHG) emissions. These emissions come from manufacturing, processing and applying fertilizers and pesticides, from fossil fuels required in field operations for soil cultivation, spreading agrochemicals, harvesting and machinery production. The majority of these GHG emissions come from nitrogen fertilizer usage. There are not only GHG emissions associated with N fertilizer manufacture but also direct and indirect GHG emissions from N application to soil. Direct emissions of N_2O result when excess N fertilizer undergoes incomplete denitrification. In addition, indirect N_2O emissions can result outside of the farm boundary when nitrate lost from the field through leaching is subsequently incompletely denitrified (Charles et al., 2006; Snyder et al., 2009; Williams et al., 2010; Linquist et al., 2012). GHGs cause chemical changes to the atmosphere and therefore contribute to Global Warming (GW). To establish a comprehensive assessment of overall GHG emissions during all off-farm and on-farm practices, a Life Cycle Assessment (LCA) (Consoli et al., 1993) should be applied to provide reliable information on the Global Warming Potential (GWP) per unit of crop production area. However, for planning more environmental friendly cereal cropping systems an assessment of both GHG emissions and crop yield per unit of crop production area is essential. Hence, GWP can also be related to the amount of a crop and be expressed per unit of grain yield. This is yield-scaled GWP (van Groenigen et al., 2010).

One of the most important cereals in world food production is wheat (881 million tons in 2016, FAOSTAT, 2018). Poland is a substantial contributor to worldwide wheat production. Especially popular is winter wheat (*Triticum aestivum L*). The Statistics Poland (GUS) reports that from 1999 to 2015 annual winter wheat production increased by 28%, from 9.0 to 11.6 million tons, with average grain yield increase from 3.5 to 4.8 t ha^{-1}, while the wheat production area was reduced by 9%. Still, this relatively low average yield is mainly due to the economical limitations of many Polish farms. When nutrient supplies in the

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form of fertilizers, pests, weeds, and diseases are effectively managed, cultivars are carefully selected, crop growth is determined mostly by plant available water during the growing season, soil properties influencing the available-water holding capacity, and by solar radiation and temperature (Edreira et al., 2017). This is the case in intensive crop production where high wheat yields (9.0 t ha^{-1}) in Polish agricultural conditions are achieved in high-yielding treatments and are comparable to yield in areas such as Germany (9.5 t ha^{-1}), which employs the world's most intensive agronomic management. Consequently, on the one hand the process of winter wheat grain production contributes to GW and on the other, wheat growth is vulnerable to negative impacts of climate change such as increasing temperatures, more extreme weather and more variable rainfall patterns (Pachauri et al., 2014; Mase et al., 2017; Mäkinen et al., 2018).

A number of studies have been conducted using LCA to calculate the yield-scaled GWP of winter wheat production (Hillier et al., 2009; Chen et al., 2014; Wójcik-Gront and Bloch-Michalik, 2016). This study, however, focuses on drivers of variation in yield-scaled GWP in intensive wheat production based on supplementary variables to those included in GWP calculations (Wójcik-Gront and Bloch-Michalik, 2016). The variables studied relate to weather, soil, winter wheat cultivar and crop management and come from long term experiments across the whole of Poland. Identifying those variables benefits sustainable wheat cropping systems by providing management practices that maximize crop productivity, while simultaneously minimizing negative environmental impacts (Grassini and Cassman, 2012).

Of the major cereal crops, wheat accounts for one of the largest global consumptions of N fertilizer (Heffer, 2013). Higher N inputs offer the potential for increases in yield. On the other hand, nitrogen fertilizer application has been recognized as the key factor for increasing N_2O emissions from the agricultural sector. Wójcik-Gront and Bloch-Michalik (2016) report that the largest impact on GWP in Polish cereal production came from applying N fertilizer (avg. 68%) and when N fertilizer use was increased by 40 kg ha^{-1} that led to higher values of yield-scaled GWP. This might suggest inefficient N use. On that account, the analysis presented in this study investigates if nitrogen was indeed an important driver of yield improvement in comparison to other environment and management related variables.

Both quantitative and qualitative variables were used to study the variability of yield-scaled GWP and yield. In the whole analysis, 6 qualitative and 14 quantitative variables were used. To analyze such a mixture of variables and the large, unbalanced amount of observation units classic statistical methods might fail to find meaningful agricultural patterns. Thus, to select the most influential variables, the classification and regression tree (CART) and random forest (RF) (Breiman et al., 1984; Tulbure et al., 2012) methods were used. As these methods are relatively new in this research field, this manuscript evaluates the potential for CART and RF to inform agronomic management decisions along with determination if environmental conditions are indeed so important in intensive winter wheat production.

2. Materials and methods

2.1. Yield experimental data

Yield data were gathered from the Polish Post-Registration Variety Testing System (PRVTS, 2018), which evaluates the yield and other related traits of newly released cultivars in multi-environmental trials. Winter wheat yield data from 17,870 observations were used. This was associated with 75 field trial locations across the whole of Poland (Fig. 1), 7 growing seasons (from 2009/2010 to 2015/2016), 127 modern, high yielding winter wheat cultivars and two agronomical intensities. The data used in this study contained observations from moderate input intensity with mineral fertilization, seed preparation, and herbicide and insecticide use and from high input intensity with additional (40 kg ha^{-1} yr^{-1}) nitrogen fertilization, use of foliar fertilization, fungicides and growth regulators which were not applied in the moderate intensity system. In the experiments, mean application levels for the fertilizers were 107.7 kg for N ha^{-1} for the moderate intensity system and 147.4 for the high intensity one, and 53.5 kg for P_2O_5 ha^{-1} and 88.4 kg for K_2O ha^{-1} for both management intensities. In the high intensity management system average foliar fertilization was 6 kg ha^{-1}. Average herbicide and insecticide use was 1.3 and 0.2 kg ha^{-1}, respectively. Fungicides were used only in the high intensity system at the mean amount of 1.7 kg ha^{-1}. The average level of chemical seed protection was 0.3 kg ha^{-1} and growth regulators were used only in the high intensity system and were applied on average at the level of 0.8 kg ha^{-1}. Winter wheat was sown at the end of September or at the beginning of October and harvested in August. Fertilizers and crop protection were applied following standard recommendations for winter wheat production.

2.2. Data used for characterizing the environment, genes and management in winter wheat yield-scaled GWP and yield analysis

For each yield data point, weather, environmental, genetic and management variables were described (Table1). To describe the major drivers of variation in the yield-scaled GWP of winter wheat production in Poland the following variables were used:

- agro-region of Poland (Studnicki et al., 2018), from 1 to 6 (Fig. 1); These are regions with similar relative performances of cultivars. There are differences between regions in agronomic conditions and presumably in agro-technical culture differentiating the yield-scaled GWP. In the cultivar recommendation, cultivar performance is evaluated in a specific trial location. However, in many cases the trial location does not overlap with the specific farmland and this information might not be useful for wheat producers. This is why the recommendation is given for the whole agro-region where locations with similar environmental conditions are clustered (Tapley et al., 2013).
- climatic water balance – KBW for April and May, KBW for May and June and KBW for June-July during each growing season; This is water available to a plant during its crucial development phases, expressed as a difference between precipitation and evaporation, dependent on temperature, humidity, wind and solar radiation (Doroszewski et al., 2012; The Institute of Soil Science and Plant Cultivation – IUNG, 2018); this was partitioned into 16 bins from sufficient water availability > -50 mm, -50- -59 mm, …, to extreme water deficiency -190- -199 mm.
- genetic variables: cultivar utilization type (based on grain protein content, amylolytic and proteolytic enzymes activity or grain density), country of origin of cultivar, cultivar frost resistance; The cultivars tested in the Polish Post-Registration Variety Testing System are selected based on the assumption that they give high yield in Polish environmental conditions. The Polish climate is moderate and varies from maritime to continental (Graczyk and Kundzewicz, 2016) and as such is similar to that in other Central-Eastern European countries. Hence, the yield is highly differentiated regarding cultivar but it is over-exaggerated when an input variable has that many levels (in this case a genotype with 127 cultivars). Then, CART can be biased toward choosing this variable (Hill and Lewicki, 2006). Thus, instead of using cultivars, their characteristics were used.
- soil quality (valuation classes according to the soil quality evaluation system in Poland compatible with regulations of the Council of Ministers – CM, 2012); In Poland, the class reflects the agricultural value of soils, the lower the class the more fertile the soils. The main criteria for classifying soil into a given valuation class are: grain-size composition, thickness of the humus horizon and humus contents, hydrological properties of the soil, reaction and calcium carbonate contents, structure and usage of the area.