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Using a nonlinear stochastic model to schedule silage maize harvesting on Estonian farms

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ABSTRACT

Agriculture has been an important sphere of activity and a source of income for Estonians throughout their history. In Estonian climatic conditions, maize is considered a thermophilic vegetable. Relatively modest night frosts (−3 to −2 °C) in the autumn can ruin an entire harvest. The critical questions are therefore when to begin the harvesting process and what kind of machines to use in order to minimise the risk of losing the harvest and maximise the expected total yield of the silage. It is very important for farm managers to make better decisions for the prediction of agricultural output using a suitable tool. It is extremely important to increase the accuracy of forecasts. To improve scientific decision-making, in this paper, a simple nonlinear stochastic mathematical model is used to schedule the harvesting of silage maize on Estonian farms. Different model specifications are used. A computer application is developed through partnership between researchers and silage maize growers in Estonia. The model performance is analysed, specifying the harvest date, the variable productivity of harvesting machines and the different density functions of the time of the first night frosts. The analysis shows that the harvest date is an essential determinant of the potential total yield of maize silage.

1. Introduction

Maize is a substantial forage crop in Estonia. In recent years (2004–2013), the area sown with maize in Estonia has increased fivefold. In Estonian climatic conditions, maize is considered a subtropical vegetable. The maize vegetation period is fairly long. In the autumn, when the first night frosts occur, maize is still in its peak growth stage. Hence, the harvesting of maize for silage depends on the timing of the first night frosts.

The harvesting of maize also depends on the productivity of the harvesting machinery. When the productivity of the machines is low, the harvesting process takes a long time; when productivity is high, the costs of using or acquiring machinery is also very high. Consequently, when the harvesting of maize begins too early, the total silage maize yield is modest. When the harvesting process begins too late, farmers run the risk of losing their entire crop. When modelling the harvesting of maize, these circumstances should be taken into consideration. In this study, we focus on silage maize harvesting models.

In the last few decades, a number of models have been developed to simulate various aspects of maize yield and forage quality. Process-orientated, dynamic models such as CERES Maize (Jones and Kiniry, 1986), MAIZE (Muchow et al., 1990), APSIM (Carberry and Abrecht, 1991), CropSyst (Stöckle et al., 1994), SUCROS97 (Van Laar et al., 1997), STICS (Brisson et al., 1998) and WOFOST (Boogaard et al., 1998) mainly focus on maize grown for grain; as a result, only the dry matter content of grain is considered.

Since its release in 1986 (Jones and Kiniry, 1986), CERES-Maize has been widely applied in different environments to test the hypothetical consequences of various management practices. The CERES-Maize model (Jones and Kiniry, 1986; Ritchie et al., 1998; Hoogenboom et al., 2003) is a maize (*Zea mays* L.) crop growth model in the cropping system model (CSM) that is part of the Decision Support System for Agrotechnology Transfer (DSSAT) (Tsuji et al., 1998; Jones et al., 2003). The DSSAT-CSM incorporates all crops as modules using a single soil model. Reidsma et al. (2009) and Ceglar and Kajfež-Bogataj (2012) examined maize yields under different climatic conditions.

Several authors have discussed the modelling of the harvesting process in agriculture, forestry and other fields. Ferrer et al. (2008) and Bohle et al. (2010) optimised the wine grape harvesting schedule using the mixed integer linear programming model. Higgins and Muchow (2003), Higgins et al. (1998) and Higgins et al. (2004) constructed a large-scale integer programming model to optimise the harvest date, yield and net revenue of sugarcane

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production, as the harvest date of sugar cane is a key determinant of sugar yield and therefore of net revenue (Higgins and Muchow, 2003; Grunow et al., 2011; Stray et al., 2012). Some authors have discussed the harvesting process of agricultural products using general agricultural planning models (Ahumada and Villalobos, 2009; Yu and Leung, 2009; Ahumada et al., 2012; Martin et al., 2012; Tan and Ēömden, 2012). Other authors have addressed the problem of optimal harvesting in forestry (Gonzalez-Olabarria and Pukkala, 2011; Helmes and Stockbridge, 2011; Asante et al., 2012; Chen and Insley, 2012; Navarrete, 2012). Several papers devoted to the optimal harvesting of perishable products have also been written (Tixier et al., 2004; Lodree and Uzochukwu, 2008; Fu et al., 2011; Ahumada et al., 2012; Singh, 2012). Some authors have discussed the modelling of the silage maize harvesting process (Aggarwal et al., 2006; Braga et al., 2008; Nousiainen et al., 2011).

The harvest date is a key determinant in the silage maize harvesting process. The tactical maize silage production optimisation model was presented by Braga et al. (2008) using the process-based crop model CERES-Maize. This model can help producers decide which maize cycle cultivars to plant for a given planting date and can evaluate the potential biomass productivity, silage quality and harvest dates.

The modification of the FOPROQ (FOrage PROduction Quality) model from a forage grass to a forage maize model was considered by Herrmann et al. (2005). Reliable results presented in this study support the current efforts to develop FOPROQ into a harvest date (time) prognosis tool in Germany.

Other essential factors that influence the silage maize harvesting process are early frosts. Crop failure due to frost was accounted for mechanistically by the CERES-Maize crop model (Ritchie et al., 1998). The impact of the early frost on silage maize harvesting has been discussed in different papers (Herrmann et al., 2005; Aggarwal et al., 2006; Braga et al., 2008).

An important obstacle to a broader and more effective use of the crop growth models is our relatively limited knowledge of uncertainty in the results of the models. Uncertainty refers to our imperfect and inexact knowledge of the world. Uncertainty is (1) an aspect of decision-making and (2) a natural consequence of limited information. Those who build models and those who depend on them should understand uncertainties in order to manage the modelling process effectively. A systematic uncertainty analysis provides insight into the level of confidence in model estimates and can aid in the assessment of how various possible model estimates should be weighted. Several papers have examined the uncertainties of the silage maize growing and harvesting models (Xie et al., 2003; Põldaru and Roots, 2006; Bert et al., 2007; Dangl and Wirl, 2007; He et al., 2010; Hyytiäinen et al., 2011).

The purpose of this study is (1) to provide insight into the structure of the silage maize harvesting model where the date of arrival of the first frost is a random variable; (2) to analyse the behaviour of the model for different values of the independent (decision) variables; (3) to determine and analyse the objective function changes in the case of different specifications (variants); and (4) to implement sensitivity analysis by estimating silage maize harvesting model parameter sensitivity under various specifications. To the best of our knowledge, the implementation of harvesting models where the date of arrival of the first frost is a random variable has not been previously discussed in literature.

In Section 2, we describe the mathematical formulation of the harvesting process of maize for ensilage and discuss the theoretical basis of estimating the uncertainty/sensitivity of the silage maize harvesting model. In Section 3, the results of the analysis are described. We analysed 2 models: in the first model, we assumed that the date of arrival of the first frost was a random variable and had normal density; in the second model, the random variable was assigned a uniform density. The analysis was carried out in four variants; two variants using a normal random variable, and two variants using a uniform random variable. In Section 3.4, we described the results of the sensitivity analysis. Section 4 presents conclusions with a summary of the specific findings.

2. Materials and methods

2.1. Study area

Our study area is Estonia, a country in the north-western part of Europe and situated on the East European Plain. The territory of Estonia covers 45,227 km^2. The most important branch of agricultural production is livestock farming with the biggest share belonging to dairy farming: milk products constitute 47% of total livestock production. Milk has always been the most important product of the Estonian agricultural sector. In recent years, milk production and milk production per cow has greatly increased. In 2013, 763.3 thousand tons of milk was produced and the average yield per cow amounted to 7824 kg (Statistics Estonia, 2014). The intensification of milk production in dairy cows needs to pay more attention to the feed base. One of the most important crops for dairy cows in ensuring a perfect ration is maize for silage. In recent years, silage maize production and the sown area have increased exponentially. This has been made possible due to the fact that the world has developed a lot of new of maize varieties that are suited to cooler climate areas. The area sown with maize and production is described in Table 1.

During the past 10 years, maize acreage has increased fivefold and output sevenfold. Maize cultivation and the feeding of maize to cattle has increased and will continue to do so. Therefore, it is important for farmers to solve problems related to the optimal harvesting time of the maize for silage.

2.2. Stochastic model of total yield of silage maize

A brief description of the mathematical formulation of the harvesting process of maize for ensilage is presented herein. The target function y in the general formula can be described as follows:

$$y = f(p_1, p_2, \ldots, p_k, x_1, x_2, z, t) \tag{1}$$

where y is a random variable (silage maize output); $p_1, p_2, \ldots, p_k$ are parameters of the model; x_1, x_2 are decision variables (x_1 is the start of the harvesting process, x_2 is the daily productivity of the harvesting machines); z is a random variable (the time of the first night frosts) and t is a time variable.

As the total yield of the silage maize and the expenditures for the acquisition of machinery have different dimensions, the target function should be expressed in terms of monetary value. The target function y (expected monetary value) will be the following:

$$y = Q_1 - Q_2 - Q_3 \tag{2}$$

where Q_1 is the expected total yield of silage maize expressed in a currency (e.g., Euros); Q_2 is the expected loss of total yield of silage maize due the first night frosts in the same currency and Q_3 is the expected annual spending on harvesting machines.

The expected total yield of silage maize Q_1 is then expressed as:

$$Q_1(t, x_1, x_2) = \int_{x_1}^{x_{1e}} p x_2 f(t) dt \tag{3}$$

where t is the current time; x_1 is the start of the harvesting process (harvest date); x_{1e} is the moment representing the end of the harvesting process; x_2 is the daily productivity of the harvesting machines; p is the unit price of silage maize and $f(t)$ is the function of silage maize yield (depending on current time).