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Water limitations on potato yield in Estonia assessed by crop modelling

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ABSTRACT

Soil moisture is one the most limiting factors for crop production. In temperate climates yields are reduced by both water deficit and excess. To calculate the impact of water limitations, alternative water balance schemes were added to the potato production model POMOD (POtato MODel) to keep the soil moisture content within its optimal range. The effects of irrigation, drainage and both together were investigated. Calculations were carried out for three Estonian locations (Tallinn, Tartu and Kuressaare) and two varieties.

For the reference run the yields were higher for the late variety and lowest in dry Kuressaare. The average irrigation requirement was 30–45 mm for the early and 47–58 mm for the late variety in continental locations, but over two times higher in insular Kuressaare. In continental stations the need for drainage was 30–40 mm per growing period in addition to natural outflow (about 20–25 mm more without outflow). In Kuressaare the mean amount of excess precipitation was only 9–20 mm and its removal had a mostly negative effect on yield due to increasing water deficit during the following dry period. In over half of the years the crops suffered from both water shortage and excess. The greatest increase in yield was achieved when both drainage and irrigation were applied. The benefit from irrigation alone was also considerable, more for the late variety and in Kuressaare. The effect of drainage was most evident in conditions of restricted outflow The negative effects of drainage on yield, as observed in years when drainage led to increasing water deficit in subsequent periods, lowered the average impact of drainage. However, in some cases the highest yield losses were observed in years with excess water.

1. Introduction

Water is one of the key resources in crop production. Its availability in soil is the result of the actions of climate/weather, soil and vegetation. Inadequate soil moisture is one of the most important stress factors for crop yield and the most limiting factor for crop production in the world (Nilsen and Orcutt, 1998). In most parts of the world, soil moisture and crop production depend on rainfall and its variability (Harpal and Graeme, 2004). Generally, the timing and amount of rainfall are uncertain, causing the stochastic behaviour of soil moisture dynamics, with fluctuation at different temporal and spatial scales. In terms of water availability, ecosystem responses are controlled by precipitation not only in terms of amount per se but also through the interaction with the soil, which control the water-holding and outflow processes. As evapotranspiration and other components of the soil water budget depend on temperature, time of the year plays a relevant role. In addition to rainfall, crop production is also considerably affected by the amount of water stored in the soil before the growing season.

Potato (*Solanum tuberosum*), a major food crop throughout the world (Scott et al., 2000), is more sensitive to water stress than many other crops and its yield and quality are reduced by relatively mild water stress (Porter et al., 1999). At the global scale the yield gap (difference between potential and actual yield) has been quantified in about 20–30 t ha^{-1} (Supit et al., 2010). To a great extent this difference is a consequence of non-optimal soil moisture.

The water limitation on crops works as a two-side process. Potato yields are reduced by both periods of water deficit and excess that are brought about by irregular rainfall (Benoit and Grant, 1980, 1985; Van Loon, 1981; Haverkort, 1982; Wright and Stark, 1990). Since yield loss due to drought is more common, especially for arid

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and/or densely populated countries, most studies on water stress of potato crops have focused on deficiencies in soil water. Different studies have shown that limited soil water availability at different stages of growth result in earlier crop maturity (Karafyllidis et al., 1996), and in decreased plant growth, tuber yield, the number of tubers per plant and tuber size and quality (e.g. Ojala et al., 1990; Lynch et al., 1995; Dalla Costa et al., 1997; Onder et al., 2005). At all stages of growth, water shortage reduces photosynthetic efficiency—but drought during the periods of stolonization, tuber initiation and yield formation (bulking) has the most drastic effect on yield (e.g. MacKerron and Jefferies, 1986; Haverkort et al., 1990; Lynch et al., 1995; Hlavinka et al., 2009).

When the soil remains excessively wet, and root and tuber needs for oxygen are not met, then potato yield and grade can also be reduced (Holder and Cary, 1984). Excess soil water is more common in temperate climates, including the Baltic Sea area, but can temporarily occur elsewhere. Excess soil water favours disease (e.g. Powelson et al., 1993; Olanya et al., 2010), leads to nitrate leaching (Roberts et al., 1991; Waddell et al., 2000) and sediment and nutrient losses in runoff. Van Oort et al. (2012) showed that in Netherlands the events with the highest impact on potato yields over a period of 60 years were a wet start or wet end of the growing season. In Northern Europe such events will probably increase with climate change (IPCC, 2007; Tammets and Jaagus, 2013). Excessive variation in soil moisture also affects potato growth. Benoit and Grant (1980, 1985) noted that periods of water deficit or excess led to severely limited potato yields in northern Maine despite total rainfall being generally sufficient.

Knowledge of potato crop water use is well established (Shock et al., 2007). Crop water use is generally considered approximately equal to evapotranspiration (Taylor and Ashcroft, 1972; Katerji et al., 2008). Potato crop potential evapotranspiration can be estimated using weather data and knowledge of the stage of potato development (Wright and Stark, 1990) and varies greatly between regions. For high yields, potato crops require 400–800 mm of water, depending on climatic conditions and growing season length (Doorenbos and Kassam, 1979; Haverkort, 1982; Wright and Stark, 1990). Tamm (1982) stated that in Estonia the average potato water demand is 240 mm during the vegetative period, more in coasts and islands, and less in middle and southern areas. Water requirements also differ depending on soil types and agricultural practices.

Since examining the yield response to different water applications is laborious and expensive, modelling can be a useful tool to study and develop irrigation strategies (Zairi et al., 2000; Benli et al., 2007; Lorite et al., 2007; Geerts and Raes, 2009; Van der Velde et al., 2010), to derive optimal irrigation quantities (Pereira et al., 2002; Liu et al., 2007) and drainage fluxes (Van der Laan et al., 2010) or to assess future changes in water resources (Frederick and Major, 1997; Murray et al., 2012) and resultant consequences for production (Olesen et al., 2011; Lehmann et al., 2013).

The purpose of the present work was to determine potential need for irrigation and drainage for potato crops under Estonian climatic conditions. Estonia belongs to the Atlantic continental region of the temperate zone, which is characterized by moderate cold winter, cool spring, a moderately warm summer and long rainy autumn but with strong variability between and within years. According to temperature conditions, Estonia is divided into two zones, of almost equal size: the northern and the middle regions, where the accumulated temperature above 10 °C is 1650–1750 degree-days; the southern and western regions and islands with 1750–1900 degree-days (Kivi, 1976). Annual sums of precipitation on average are 550–750 mm and sums of precipitation for the growing season on average are 320–380 mm (in drought years 200–300 mm) (climate data for the period 1971–2000; http://emhi.ee/?ide=6,299,303 [14.01.2014]). Since the annual amount of precipitation exceeds evaporation by a factor of two, the climate is generally excessively damp; however, there are considerable differences in precipitation between regions and years as well as within growing seasons. Due to very high variability of precipitation, drought periods as well as excessive wet periods do occur in Estonia quite often during the warm half-year. The climatological conditions allow the cultivation of one crop per year during summer with irrigation possibly needed in May–June, and in dry years also in July–August.

Potato has been an important food crop in Estonia for over 150 years. Potatoes required more work than other crops; yet, they turned out to be more profitable and thus a steady and stable source of income. After the First World War Estonia held the first place in potato growing per person in the world, and about 25% of all agricultural land was used for potato production (Aamisepp, 1931). Seed potato was one of the important export articles of Estonia (Aamisepp, 1936), which was even called a “potato republic”. Today the potato production in Estonia is decreasing. Although potato yields per hectare have increased over the last 20 years, the production area and thus total production has decreased.

One of the main reasons for the decrease in production is insufficient subsidy for agricultural production, which means that the price of domestic potato is higher compared to imported tubers. Potato production does not provide stable income for farmers any more. In such market situation, relatively unfavourable and highly variable Estonian climate, including short and relatively cold growing season and often excessive precipitation, is working as an important limiting factor for potato production. Dry periods, especially in May and during the second half of summer, are also not infrequent (Tammets, 2007). Dry and wet periods in Estonia are altering (Tarand, 1993; Jaagus, 2006) with both the number of extremely wet and extremely dry days weakly increasing (Tammets, 2007). Extreme precipitation events have already become more frequent and intense (Tammets and Jaagus, 2013). Under such circumstances, the means of soil water regulations are becoming increasingly important, if there is a will to maintain local potato production.

Currently drainage is more prevalent in Estonia than irrigation. It is estimated that without drainage about two-thirds of the land for agricultural production (1.1 million ha in 2010, about 25% of total land area) would suffer from waterlogging (Tõnismäe et al., 1998) and predicted climate change will increase the importance of proper drainage activities. By the beginning of the 1980s, over 800 000 ha of land (almost 85% of the cultivated land) was drained, of which 89% was equipped with subsurface drainage systems (Ratt, 1985; Valk, 1988). The system was not fully maintained and managed after restoration of Estonia’s independence due to changes in land ownership. Today about half of Estonian agricultural land (640 000 ha) is drained, of which about 590 000 is used in actual agricultural production (Amelioration Systems Register: http://msr.agri.ee/Aruanded.aspx [14.01.2014]). It has been estimated that the potential drained area of Estonia can reach up to 880 000 ha (Tõnismäe et al., 1998).

There is little irrigation of field crops in Estonia. Although the area equipped for irrigation reached almost 14 000 ha by the end of the 1970s, it had reduced to 2200 ha by 2013 (Amelioration Systems Register: http://msr.agri.ee/Aruanded.aspx [14.01.2014]). Most of that is two-way amelioration. Only 25 ha of irrigated potato fields were reported (Statistics Estonia, 2010).

Despite foregoing recession, many potato growers are showing increasing interest to learn about the needs and possibilities to alter soil water regime. This was the main motive for our research. Since long-term experimental studies of the effect of water shortage and excess cannot be easily conducted, the task was addressed by a crop