Field Crops Research 118 (2010) 183–193

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Multivariate analysis of relationship between potato (*Solanum tuberosum* L.) yield, amount of applied elements, their concentrations in tubers and uptake in a long-term fertilizer experiment

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ARTICLE INFO

Article history:
Received 10 December 2009
Received in revised form 20 May 2010
Accepted 24 May 2010

Keywords:
Arsenic and lead
Heavy metals
Nitrogen, phosphorus and potassium fertilizers
Pig slurry
Redundancy analysis
Illimerized Luvisol
Trace and risk elements

ABSTRACT

The aim of this study was to investigate how potato yield, the concentrations of elements (N, P, K, Ca, Mg, S, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) in tubers and their uptake are affected by mineral N, P and K fertilizers, straw and pig slurry application.

Potatoes were collected in 2008 from the Ruzyně Fertilizer Experiment (RFE, the Czech Republic, 24 fertilizer treatments), which was established on a permanent arable field (Illimerized Luvisol) in 1955. Fifty-three years of fertilizer application have resulted in highly contrasting levels of P and K availability in the different treatments. A plant available (Mehlich III) soil P concentration below 30 mg kg^{-1} and a K concentration below 150 mg kg^{-1} were not adequate for satisfactory tuber production. No positive effect of long-term straw application on tuber yield was recorded. The optimal application rate of mineral fertilizers resulting in a tuber yield above 30 t ha^{-1} was 140 kg N ha^{-1}, 63 kg P ha^{-1} and 186 kg K ha^{-1}. The highest environmentally acceptable N application rate for potatoes was 120 kg N ha^{-1}, applied in the form of mineral fertilizer. Substantially higher production efficiency was recorded for mineral N, P and K fertilizers than for pig slurry. The concentrations of As, Cd, Cr, Cu, Fe, Mn, Pb and Zn in tubers were not significantly affected by fertilizer treatment although pig slurry supplied substantially higher amounts of Cu and Zn to the soil than were taken up by the tubers. The concentration of Pb exceeded the Czech legislation DM limit (0.61 mg kg^{-1}) in 83% of samples, but there was no significant effect of fertilizer treatment. Therefore normal cropping practices do not significantly increase the concentrations of trace elements in potatoes.

1. Introduction

The potato (*Solanum tuberosum* L.) is one of the most important agricultural crops in the world. In the Czech Republic, it is a staple food crop with an average annual consumption of 74 kg tubers per capita in 1999–2006 (CSO, 2009), and a cropping area of 30 000 ha representing 0.8% of total agricultural land in 2008 (CSO, 2009). In addition to areas recorded in official cropping statistics, potatoes are frequently planted on private gardens covering approximately 5000 ha. The average potato yield increased substantially from 11 t ha^{-1} in the 1920s to 23 t ha^{-1} in the period from 2000 to 2008 (CSO, 2009). The increase in potato yield was substantially lower in the Czech Republic than in Germany (with comparable soil and climatic conditions) due to the lower NPK application rates and poorer crop protection in the last few decades. In Germany for example, the average yield of potatoes was 36 t ha^{-1} in 2000 (Chloupek et al., 2004). This is substantially higher than the world average yield, estimated at 17 t ha^{-1} for the last decade (FAO, 2009).

Potato yield is greatly affected by nutrient availability, which is why research on appropriate fertilizer regimes has received much attention worldwide (Hamouz et al., 2005; Westermann, 2005; El-Sirafy et al., 2008; Kulhánek et al., 2008; Poljak et al., 2008; Vos, 2009). Phosphorus fertilizer application increased the total tuber yield and yield of undersized tubers below 85 g but decreased the proportion of large-sized tubers above 285 g in a study by Rosen and Bierman (2008). Increased tuber number with P application has been reported by many authors (Freeman et al., 1998; Jenkins and Ali, 2000; Maier et al., 2002). Inadequate N fertilization leads to poor potato growth and yield, while excessive N application leads to delayed maturity, poor tuber quality, excessive nitrate leaching and occasionally a reduction in tuber yield (Sharifi et al., 2005; Li et al., 2006; Zebarth et al., 2006; Haase et al., 2007; Kumar et al., 2007; Sincik et al., 2008; Arriaga et al., 2009; Černý et al., 2010).

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0378-4290/$ – see front matter
doi:10.1016/j.fcr.2010.05.009

The long-term application of various fertilizers can increase the concentration of trace elements (heavy metals especially) in plant biomass because many fertilizers contain trace elements or increase their mobility in the soil (Keller and Schulin, 2003; Micó et al., 2006; Hejcman et al., 2009). The cadmium concentration in potatoes has received much attention as tubers accumulate Cd; thus their consumption in high quantities contributes substantially to human dietary Cd intake in many countries (McLaughlin et al., 1997). The concentration of Cd in plant tissues is a function of the plant available Cd concentration in the soil (Panwar et al., 1999). This may be high, especially on soils with a pH (H_2O) ranging from 4.5 to 5.5, which is why a negative correlation between Cd concentration in tubers and soil pH was recorded by Smith (1993). Lime application increases soil pH and can be used to decrease Cd availability on acid soils (Lee et al., 2003; Vaněk et al., 2005). As well as on acid soils, a high Cd concentration has frequently been recorded in potatoes grown on saline neutral or alkaline soils, because the high Cl^- concentration in the soil solution mobilizes soil Cd and increases the availability of Cd to plants (McLaughlin et al., 1994; Maier et al., 1997; Smolders et al., 1998). Research on As, Cr and Pb concentrations in potatoes has received substantially less attention than that of Cd, although all these elements are highly toxic to crops as well as to humans (Gichner et al., 2006; Pruvot et al., 2006; Luan et al., 2008; Safari Sinegani and Khalilikhah, 2008; Vácha et al., 2008; Zhuang et al., 2009).

The aim of this study was to investigate how the yield of potato tubers, and the concentrations of macro (N, P, K, Ca, Mg and S) and trace (As, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) elements in tubers are affected by long-term fertilizer application on Illimerized Luvisol. Further, we investigated a simplified balance of elements to reveal whether the amount of elements applied in fertilizers exceeds the amount removed in the harvested potatoes. Using the ordination approach, the final aim of the study was to determine how the concentrations and uptake of elements and potato yield are related.

2. Materials and methods

2.1. Site description

The Ruzyně Fertilizer Experiment (RFE) was established on a permanent arable field in 1955, on the western edge of Prague, the capital of the Czech Republic (50°05′15″N; 14°17′28″E).

At the study site, the mean annual temperature is 8.2 °C (ranging from 6.4 to 9.7 °C) and the mean annual precipitation is 422 mm (ranging from 255 to 701 mm; Prague-Ruzyně Meteorological Station, 1955–2007). According to the Czech taxonomic soil classification system (Němeček et al., 2001) the soil type was classified as Illimerized Luvisol (syn. Illimerized Gray-brown Soil). The parent material is loess mixed with highly weathered chalk. The ground water level is 20 m below the field surface. The upper 30 cm (arable layer) contains 27% clay, increasing to 40% in the subsoil (soil layer 30–40 cm) and 49% at 40–50 cm depth. The soil pH (H_2O) was 6.5 in the top 20 cm before establishment of the experiment in 1955.

2.2. Experimental design

The Ruzyně Fertilizer Experiment (RFE) is a large scale experiment consisting of five field strips (Fig. 1). Each field strip consists of 24 fertilizer treatments replicated four times and arranged in a complete randomized block design (96 individual plots). The individual plot size is 12 m × 12 m and only the central 5 m × 5 m plot has been used for experimental purposes. In this study, potatoes were only sampled from strip number I, named the "Cereal Crop Rotation" (67% cereals, 11% root crops and 22% legumes). The crop sequence was alfalfa, alfalfa, winter wheat, winter wheat, spring barley, potatoes, winter wheat, winter wheat and spring barley with alfalfa under-sowing. In the experiment, the following mineral fertilizers were applied directly to the potatoes: calcium ammonium nitrate (27% N) at the rates of 80 kg N ha^{-1} (N1), 100 kg N ha^{-1} (N2), 120 kg N ha^{-1} (N3) and 140 kg N ha^{-1} (N4); super phosphate (8.3% P) at the rates of 43 kg P ha^{-1} (P1) and 63 kg P ha^{-1} (P2); potassium chloride (49.8% K) at the rates of 133 kg K ha^{-1} (K1) and 186 kg K ha^{-1} (K2). In treatments with straw application marked as sII, 80% of N was applied as calcium ammonium nitrate and 20% as ammonium sulfate.

The following organic fertilizers were also used: straw at low (sI) and high application rates (sII) and pig slurry mixed with straw (PSs). Pig slurry was applied in the autumn before planting the root crops. A list of treatments and the amount of elements applied directly to the potatoes are given in Table 1. The mean annual application of elements over all crops is given in Table 2.

The concentrations of elements in the mineral fertilizers used to calculate the application rates were taken from Uprety et al. (2009). Three samples of pig slurry for chemical analyses were collected

Fig. 1. Aerial photograph of the Ruzyně Fertilizer Experiment (RFE) established in 1955. Latin numbers (I–V) indicate remaining experimental strips. Potatoes were planted in strip number I in 2008. Five experimental strips were lost due to highway construction in the 1990s. The runway center-line lights in the bottom left hand corner of the photograph indicate the close vicinity of the international airport Prague-Ruzyně.