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Effect of long-term phosphorus fertilization on soil Se and transfer of soil Se to crops in northern Japan

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HIGHLIGHTS

- P fertilizer can be the source of Se for agricultural crops.
- P fertilizer can increase Se availability for crops.
- Excessive P fertilizer use is common in developed country.
- We examine the effect of P fertilizer on soil and plant Se in field.
- Excess P fertilization in Japan contributes to increased Se uptake by crops.

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ABSTRACT

Phosphorus (P) fertilizer can potentially serve as a source for Se accumulation in croplands. Furthermore, it has been reported that the addition of P fertilizer to soil may enhance Se availability. Japanese agricultural soils are typically enriched in P as a result of long-term, excessive P fertilization. Therefore, we conducted a three-year field experiment in order to evaluate the effect of P fertilization on the Se content of soils and crops. Potato, wheat and barley were cultivated with and without P fertilization at two field sites in Hokkaido (northern Japan) with different levels of historical P accumulation. The first field site consisted of an Andosol soil with low available P and the second site, a Cambisol soil with high available P. The three years of continuous P fertilization over the course of the experiment did not result in a significant increase in the Se content of soils or plants. The Se content of soils and plants, however, was higher in soil samples from the Cambisol field site than from the Andosol field site, and total soil Se was significantly correlated with available soil P. Soluble soil Se and the soil–plant transfer factor for Se were not affected by P fertilization. Thus, we concluded that the higher plant Se content at the Cambisol field site was primarily due to the higher levels of accumulated Se in the soil at the site and that historical excess P fertilization typical of agricultural soils in Japan contributes to increased Se uptake by crops.

1. Introduction

In most soils, selenium (Se) is a naturally occurring trace element. Although Se is an essential nutrient for animals, it can also be toxic to them when it occurs at high concentrations in soil, water, or plants (Ohlendorf, 1989). Thus, Se has been listed as a priority pollutant by the US Environment Protection Agency (US EPA) (Keith and Telliard, 1979) and much attention has been paid to its biogeochemistry and behavior in the environment. Numerous studies have shown that application of Se to soil can promote plant growth by increasing the activity of antioxidant enzymes (Djanaguiranman et al., 2005). The Se content of crops has received considerable attention in recent years because of its importance in the food chain and because of its effects, both beneficial and harmful, on plants and animals.

Meanwhile, it is known that fertilizers may contain trace element contaminants such as cadmium or uranium that can be inadvertently introduced into soils (Mortvedt, 1996; Takeda et al., 2005). In particular, phosphorus (P) fertilizer, applied over the long-term, can serve as an important source of trace elements such as arsenic, cadmium and lead that can potentially accumulate in plants and soils. Se is also found in P fertilizer (0.5–25 mg Se kg^{-1} P fertilizer, He et al., 2004). The behavior of these trace elements is influenced substantially by soil management (Jiao et al., 2013).

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Table 1
Crop rotation system and fertilizer (kg ha^{-1}) regimen for the two field sites used in the experiment from 2009 to 2011.

	2009			2010			2011			Total P input (kg P ha^{-1})	Total Se input (mg Se ha^{-1})[a]
	N	P	K	N	P	K	N	P	K		
U-A field site	Sugar beet			Potato			Winter wheat				
NPK	160	109	133	100	79	108	100	65	83	253	1418
P 1/2	160	55	133	100	39	108	100	33	83	127	709
-P	160	0	133	100	0	108	100	0	83	0	0
-P-K	160	0	0	100	0	0	100	0	0	0	0
Y-C field site	Sugar beet			Potato			Barley				
NPK	160	109	133	100	79	108	60	44	66	231	1296
P 1/2	160	55	133	100	39	108	60	22	66	116	648
-P	160	0	133	100	0	108	60	0	66	0	0
-P-K	160	0	0	100	0	0	60	0	0	0	0

[a] Se input was calculated based on Se concentration in P fertilizer of 0.44 mg Se kg^{-1}.

In Japan, most agricultural land has high levels of P due to excessive use of P fertilizer (Mishima et al., 2010). Therefore, it is speculated that P fertilization is a factor controlling Se uptake in crops. In upland soils, Se forms selenate (SeO_4^{2-}) and selenite (SeO_3^{2-}) (Lauchli, 1993; Zayed et al., 1998; Terry et al., 2000). However, in acidic soil, selenate is unstable and easily leached (Neal et al., 1987a,b). Thus, selenite is considered to be the primary Se form in acidic soils (Asagawa et al., 1977). Yamada et al. (1998) reported that the major component of NaOH-extractable Se in Japanese soils was selenite, which has a lower solubility than selenate. A radioactive tracer study using ^{75}Se added to Japanese soils showed that 80–100% of added ^{75}Se tracer with selenite form carrier was adsorbed to oxy-hydroxides of Al or Fe as ligand-exchangeable forms (Nakamaru et al., 2005). As such, it has been suggested that, (i) Se can accumulate in acidic upland soils as ligand-exchangeable selenite as a result of P fertilization and (ii) that this ligand-exchangeable Se is available to plants given that it can be exchanged by phosphate ions (Dhillon and Dhillon, 1999; Zhao et al., 2005; Nakamaru et al., 2006). Though many studies suggest that P fertilizer can increase Se uptake by crops, little is known regarding the influence of P fertilization on Se behavior in field soil. The purpose of the present study is to determine the effect of long-term P fertilization on soil Se and transfer of Se to crops in agricultural fields.

2. Materials and methods

2.1. Study area

In order to study the effect of P fertilization on major and trace elements in plants and soils, a field experiment was conducted in the northern area of Japan (Abashiri, Hokkaido Prefecture, 44.0° North, 144.2° East). The experiment was conducted from May 2009 to November 2011. Evaluation of soil and plant Se was started in 2010. Two fields were used in the study: one in the Urashibetsu area (U-A field) and the other in the Yasaka area (Y-C field). The soils of these two fields are classified according to the FAO-UNESCO classification system (FAO-UNESCO, 1990) as an Andosol and a Cambisol field, respectively. These two soil types are typical in upland fields in northern Japan. The two areas were chosen due to substantial differences in their available P levels. The Y-C field had been cultivated since 1925, while the U-A field was converted from forest land starting in 1983. Consequently, the U-A field had relatively lower available P content than the Y-C field, which had experienced long-term P fertilization.

2.2. Field experiment

Consistent with the major crop rotation used in the study area, in the field experiment, sugar beet (*Beta vulgaris* ssp. *vulgaris*), potato (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) were cultivated. To evaluate the effect of fertilization on soils and plants, four fertilization methods (in separate plots) were used: (i) conventional NPK application (NPK), (ii) P fertilization at half the conventional rate (P1/2), (iii) no P fertilization (-P), and (iv) no P and no K (-P-K). The fertilization methods constituting the experimental treatments and crop rotation system are summarized in Table 1. These four treatments were applied as four replicates in a randomized block design, resulting in a total of 16 experimental plots each in both U-A and Y-C fields. Nitrogen (N) was added as Chilean saltpeter for sugar beet and as ammonium sulfate for the other crops. P and K were added as superphosphate and potassium chloride, respectively. The Se content of N and K fertilizers was below than detection limit (0.5 μg Se kg^{-1}>). The Se input at the two field sites resulting from P fertilization is also shown in Table 1. The mean annual P and Se input due to chemical fertilizer were 80.7 kg P ha^{-1} year^{-1} and 452 mg Se ha^{-1} year^{-1}, respectively. The level of P input was set equal to the mean P input in upland fields in Japan. According to Mishima et al. (2010), while mean P input to Japanese upland fields declined from 124.1 kg P ha^{-1} year^{-1} in 1985 to 83.6 kg P ha^{-1} year^{-1} in 2005, the fertilization level is still high. We assume that the level of Se input observed in this study is equal to the level normally occurring in Japan.

Soil samples taken from a depth of 0 to 20 cm were collected from each of the 16 plots in both field sites; soil sampling was done in late spring or early summer after sowing (May or June) in 2010 and 2011.

2.3. Analysis of soil and plant samples

For soil samples, available P, total P, and total Se and soluble Se amount were measured in 2010 and 2011. The available soil P was extracted by the Truog method using a pH 4 $(NH4)_2SO_4$–H_2SO_4 solution (Truog, 1930, modified by Blakemore et al., 1981). We chose this method because it is the method that is most commonly used for evaluation of available soil P in Japan. Exchangeable K amount was determined by the Schollenberger method (Schollenberger and Simon, 1945). The P adsorption coefficient (mg P_2O_5 adsorbed to 100 g of soil) was determined by adding 50 mL of a 2.5% $(NH_4)_2HPO_4$ solution to 25 g of air dried soil, shaking the resulting suspension for 24 h, and then measuring the P concentration of the solution. Soil Se was measured by Atomic Absorption Spectrometry (Thermo Fisher, iCE 3000) and a hydride generation system (Thermo Fisher, HYD-10) following digestion of the sample with $HClO_4$–HNO_3-HF. Plant samples were digested using a similar method, and Se concentration was determined by ICP-MS (Yokogawa Analytical Systems, Agilent 7500c). Plant Se uptake was determined by multiplying the Se concentration and the dry