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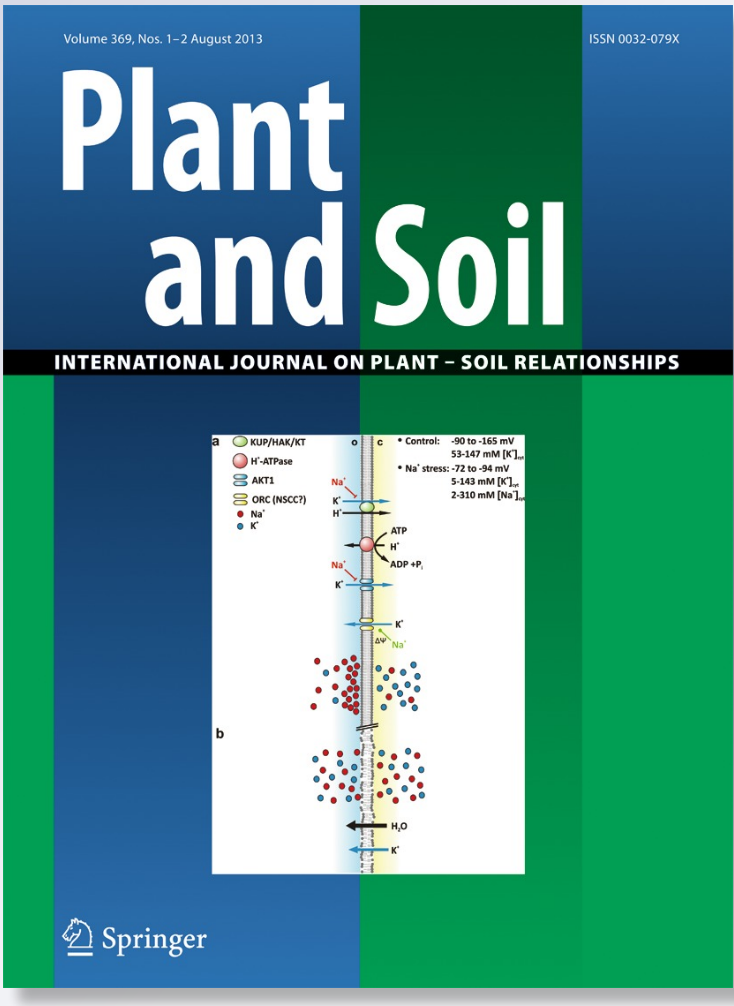

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REGULAR ARTICLE

Prehistoric settlement activities changed soil pH, nutrient availability, and growth of contemporary crops in Central Europe

Michal Hejcman · Kateřina Součková · Martin Gojda

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Abstract
Background and aims How prehistoric human settlement activities have changed soil chemical properties, plant nutrition and growth of contemporary crops is a question that has not been satisfactorily addressed. The aim of this paper was to study to what extent nutrient availability in the soil, together with nutrition and growth of spring barley (*Hordeum vulgare*), improved on sites of former sunken buildings (cropmarks) in comparison to their surroundings (controls) 1,700 years after abandonment of the buildings.
Methods In the Czech Republic, a unique prehistoric settlement with many sunken buildings was discovered during aerial reconnaissance from cropmarks in stands of cereals. Soil and biomass samples were collected from cropmarks and controls in a barley crop in June 2012.
Results A substantially higher content of organic matter, higher pH and concentrations of plant-available (Mehlich III) P, Ca, Mg, Cu and Zn were recorded in the sub-soil layer in cropmarks compared with controls, indicating the accumulation of wood ash and organic waste. In the arable layer, pH and concentrations of P, Ca and Mg were generally very high in both positions. Cropmarks were characterised by barley plants that were twice as tall as the controls, with significantly higher Ca, Mg and P concentrations.
Conclusions Prehistoric settlement activity affected nutrient availability and plant growth in the previously settled area even after 1,700 years. We conclude that the chemical signature of prehistoric settlement activity can be detected from chemical analysis of the sub-soil layer as well as analysis of the contemporary arable layer and crop biomass.

Keywords Aerial archaeology · Cropmarks · Plant nutrition · Spring barley (*Hordeum vulgare*) · Sunken buildings

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Highlights: Prehistoric settlements can be identified by cropmarks in current crops. The chemical signature of settlement was detected in soils and crops after 1,700 years. The dimensions of prehistoric sunken buildings can be estimated from improved growth of spring barley (*Hordeum vulgare*).

M. Hejcman (✉) · K. Součková
Department of Ecology, Faculty of Environmental Sciences, Czech University of Life Sciences,
Kamýcká 129,
CZ-165 21 Prague 6, Suchdol, Czech Republic
e-mail: hejcman@fzp.czu.cz

M. Hejcman
Institute of Prehistory and Early History, Faculty of Arts, Charles University,
Náměstí Jana Palacha 2,
CZ-116 38 Prague 1, Czech Republic

M. Gojda
Department of Archaeology, University of West Bohemia,
Sedláčkova 15,
CZ-306 14 Plzeň, Czech Republic

M. Gojda
Institute of Archaeology, Czech Academy of Sciences,
Letenská 4,
CZ-118 01 Prague 1, Czech Republic

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Introduction

How prehistoric human settlement activities changed soil chemical properties, plant nutrition and growth of contemporary crops is a question that has not been satisfactorily addressed. This is due to an almost complete lack of interdisciplinary research integrating archaeology with chemical analyses of soils and biomass and plant nutrition research (Hejcman et al. 2011). It is known that ancient human settlement activity can lead to the accumulation of nutrients in settled areas (Wells et al. 2000; Fernández et al. 2002), due to the transport of organic materials such as human and animal foodstuffs, together with fire and construction wood from the surrounding landscape into settlements (Kuna et al. 2004; Salisbury 2012). Large amounts of nutrients can also be transported directly in the digestive tract of livestock which graze the vegetation surrounding settlements during the day and deposit nutrients in the form of faeces in settlements at night—a principle known as "paddock manuring" (Hejcman and Schellberg 2009). Further sources of nutrients are human faeces, human and animal cadavers, bones of eaten animals and other organic and inorganic waste, particularly biomass ashes (Semelová et al. 2008; Gojda and Hejcman 2012). On the landscape level, the transport of organic materials leads to slight nutrient depletion in the area surrounding settlements on one hand and to high nutrient accumulation within settlements on the other. For example, high nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and zinc (Zn) availability together with alkaline soil pH have been measured in contemporary arable soil and sub-soil waste pits by Hejcman et al. (2011) in a village abandoned in the thirteenth century. In this medieval village, sub-soil waste pits were identified from positive "cropmarks" (improved crop growth and nutrition) overlying them in the stand of winter wheat (*Triticum aestivum*).

Phosphorus is unique among elements in being a sensitive and persistent indicator of human settlement activity because of its accumulation in the soil profile in various forms and also due to its highly restricted leaching in comparison to many other elements (Holliday and Gartner 2007; Wells and Terry 2007; Roos and Nolan 2012). In deserted settlements, carbon (C) and N can also accumulate in the form of soil organic matter, as well as Ca, Mg, K, Cu and Zn, but analysis of these elements at archaeological sites has received substantially less attention than the analysis of soil P (but see Linderholm and Lundberg 1994; Dupouey et al. 2002; Dambrine et al. 2007; Hjulström and Isaksson 2009; Oonk et al. 2009).

In Europe, deserted settlements on contemporary arable land can be identified by cropmarks which are clearly visible on aerial photographs. Positive cropmarks most frequently indicate sub-soil waste pits, sunken buildings, graves and ditches (Gallo et al. 2009; Aqdus et al. 2012; Gojda and Hejcman 2012). Alternatively, negative cropmarks, which are areas of depressed crop growth above archaeological features, often indicate the presence of stony constructions in sub-soil and former roads (Evans and Jones 1977; Doneus 2001; Hejcman and Smrž 2010). Decades of deep ploughing can disturb the fine-scale pattern of soil chemical properties created by ancient human activity, but this pattern can be well preserved in the sub-soil or as a "rough" large-scale pattern in the contemporary arable layer (Hejcman et al. 2011; Roos and Nolan 2012).

In the Czech Republic, a unique prehistoric settlement with many sunken buildings (sometimes referred to as sunken huts, sunken-featured buildings, Grubenhäuser or pit houses) was discovered during aerial reconnaissance based on positive cropmarks in stands of cereals in 1992. Sunken buildings are one of the commonest types of archaeological evidence for open settlements in Central Europe from the Late Iron Age until the beginning of the Early Middle Ages (the third century BC to the seventh century AD; Gojda 1997). Until the end of the Iron Age, they were usually considered to be typical residential buildings of the Celtic population (Venclová 2007). Since the first century AD, during the time of the Roman Empire, they were spread over the *Germania magna* (syn. *Germania libera*). These terms were used in Latin texts by Roman historians (such as Tacitus and Velleius Paterculus), to denominate the territory outside the Roman Empire occupied predominantly by Germanic tribes (Salač 2008; Salač and Bemmann 2008). Sunken buildings were also extensively used in the period when the first Slavic population arrived in Central Europe from the East (the Early Slavic period in archaeological terminology is the sixth to seventh centuries AD; Gojda 1991; Šalkovský 2001). This type of building construction continued in a limited way until the Late Medieval period (the fourteenth to fifteenth centuries; Vařeka 2004). Consequently, the three largest population groups which have established

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the ethnic and cultural foundation of contemporary Europe all constructed sunken buildings and used them as residential features, therefore, rectangular cropmarks that indicate the position of former sunken buildings can be recorded throughout almost the whole of Europe (Tipper 2004; Vařeka 2004; Droberjar et al. 2008).

The aim of this paper was to study to what extent nutrient availability in the soil, together with nutrition and growth of spring barley (*Hordeum vulgare*), improved on sites of former sunken buildings in comparison to their surroundings, 1,700 years after their abandonment.

We asked the following research questions: (1) What are the differences in soil chemical properties in arable and sub-soil layers between cropmarks that indicate former sunken buildings and their surroundings? (2) What are the differences in the height of spring barley and its biomass chemical properties growing in either cropmarks that indicate former sunken buildings or in their surroundings? The results obtained are discussed in the context of prehistoric farming practices in Central Europe.

Materials and methods

Study site

The area of the prehistoric settlement was discovered on 24 June 1992 as one of the first cropmark sites identified and documented by M. Gojda during the first air-survey campaign performed by the Institute of Archaeology of the Czech Academy of Sciences in Bohemia, the western part of the Czech Republic (Gojda 1997). The cropmark features were spread over an area of about 25 ha near the village of Radonice, 10 km east of Prague (at an exact position of 50°8′ 51.55″N and 14°36′1.96″E). Between 200 and 250 archaeological point features were discovered according to positive cropmarks on arable fields and were documented by aerial photographs taken in the summers of 1992, 2000, 2011 (Fig. 1) and 2012 (Fig. 2a). Typologically, there were postholes, which usually indicate the remains of former aboveground buildings, waste pits and sunken buildings. The discovered settlement is one of the largest late prehistoric settlement areas ever recorded in Bohemia.

The site is located on a local plateau above the confluence of the Vinoř stream and a local unnamed brook at an altitude of 250 ma.s.l. The difference in elevation between the stream valley bottom and the plateau-top is 15 m. The geological substratum is sand on which haplic cambisol has developed, with an arable layer depth of 30 cm. At the study site, the mean annual temperature over the last 50 years has been 9 °C and mean annual precipitation, 600 mm.

Fig. 1 Aerial oblique photograph of the Radonice prehistoric settlement area discovered by cropmarks in cereals photographed in June 2011. The level of visibility of all features was more or less the same as in June 1992 and 2012. Rectangular cropmarks indicate the position of former sunken buildings. Numbers 1–4 indicate selected cropmarks for the analysis in this paper (photograph by M. Gojda)

The quantity of archaeological features and their frequent superimposition on top of each other indicates that the site was settled for a long period of time. This has been confirmed by results obtained from two campaigns of surface artefact collection in 1992 by M. Gojda and in 2000 by V. Daněček (Fig. 2d). Artefacts collected during the 1992 plough-walking survey suggest that the area was probably settled as early as the Neolithic period (the fifth millennium BC) and definitely by the Iron Age (around the mid-first millennium BC). The 2002 campaign resulted in the collection of pottery fragments, most of which date to the first half of the first millennium AD, mostly to the third and fourth centuries (the Late Roman period in archaeological classification). The analysis of this artefact collection confirmed preliminary assumptions concerning dating of the largest rectangular cropmark features investigated in this study to the Late Roman period.

Data collection

In June 2012, four representative rectangular cropmarks indicating the positions of sunken buildings

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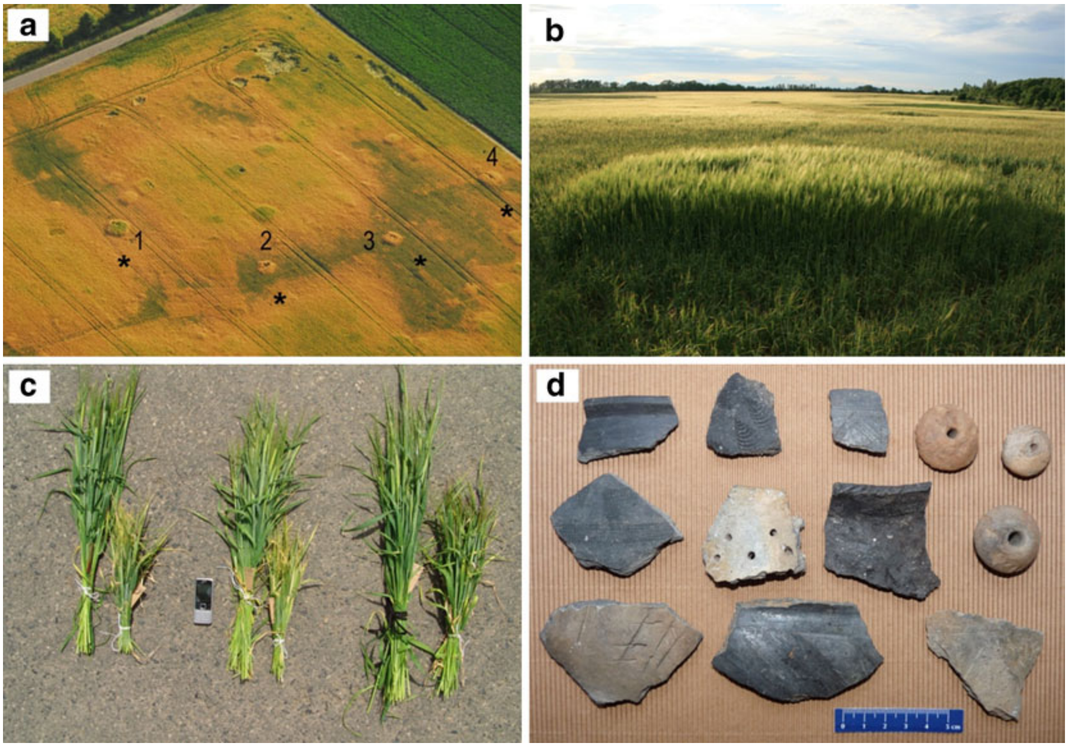

Fig. 2 **a** Aerial oblique photograph of the study site showing the numbers of investigated positive cropmarks (sunken buildings) in the spring barley stand on 29 June 2012. Position of control to each cropmark is indicated by asterisk. **b** Ground photograph of the positive cropmark above sunken building number two. **c** Samples of spring barley aboveground biomass taken in the central part of cropmarks 1–3 (taller bundles) and in surrounding controls (lower bundles). **d** Characteristic pottery fragments of the Late Roman period in Bohemia. These were collected during plough-walking campaigns (the way by which artefacts ploughed-out on a field surface are intentionally collected) of the Radonice settlement area in spring 2000. Three spindle whorls in the upper right corner of the photograph indicate textile production at the site (photographs by M. Gojda, M. Hejcman and V. Daněček)

were selected for the detailed analysis of soil and biomass chemical properties and for height measurement of spring barley (*Hordeum vulgare*) (Fig. 2). We used a "paired plots" approach to collect soil and biomass samples either from the centre of each positively-cropmarked plot (referred to as "cropmarks" in all analyses) or from the nearby surroundings within 10 m distance from cropmarks (referred to as "controls"). This resulted in sampling from eight sites i. e. four pairs of cropmarks and controls (Fig. 2a).

Ground plans of sunken buildings

According to our previous experience, the size of the cropmark corresponds well to the ground plan of sunken buildings (Gojda and Hejcman 2012). Cropmark numbers one to four were individual sunken buildings with ground plan dimensions of 4.5×5.0 m, 3.3×4.4 m, 3.6×4.0 m and 4.0×5.5 m, respectively. At archaeological sites in Bohemia, point features of rectangular ground plans with dimensions of 2.0–4.5 m×3.5–5.5 m suggest the presence of sunken buildings, as evidenced by archaeological excavations (Salač 2008). In contrast to large rectangular cropmarks, the interpretation of smaller rectangular cropmarks approximately 1.5–2.0×2.5–3.0 m in size is more difficult without excavation, as they can either represent small sunken buildings or large burial pits, whose funerary function might be supported by their occasional arrangement in parallel lines or by their identical orientation (E–W or N–S). As evidenced by cropmarks on aerial photographs, examples of all these features were recorded in the late prehistoric settlement at Radonice. We selected large rectangular cropmarks for analysis as we were able to interpret these without expensive and lengthy archaeological excavations. The depth of sunken buildings varies between a few decimetres to more than 1 m. However, this does not reflect cultural tradition, but this parameter is very

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often a result of post-depositional processes (such as colluvial erosion or the accumulation of sediments in river valley bottoms) which occurred on the site following its desertion. In the Radonice settlement, sunken buildings were deeper than 70 cm from the soil surface as we were not able to reach their floor using the soil probe.

Soil sampling and analyses

Soil samples were taken from the arable layer (0–20 cm) and from the sub-soil layer (35–55 cm), using a soil probe with a diameter of 5 cm on 8 June 2012 (Fig. 3). In cropmarks, the sub-soil layer represented infill of sunken buildings. Plant residues were removed immediately and the samples were air-dried, ground in a mortar, and sieved to 2 mm. The concentration of all plant-available elements was determined in a Mehlich III extract (Mehlich 1984) by inductively-coupled plasma optical emission spectrometry (ICP-OES). The organic C content was determined by the NIRS method. Soil pH ($CaCl_2$) was measured in a 1:5 (w/v) solution (10 g of soil+50 mL of solution) containing 0.01 mol/L $CaCl_2$ at 20 °C±1 °C. All analyses were performed by an accredited national laboratory, Ekolab Žamberk (www.ekolab.cz).

Biomass sampling and analyses

Aboveground biomass samples were collected at the milky stage of barley kernel development on 8 June 2012. The height of five representative plants was measured in 1 m^2 sampling plots at each site. In the same plot, above-ground biomass samples cut 3 cm above the ground were collected for the analysis of biomass chemical properties (Fig. 2c). The concentrations of elements in the aboveground biomass were determined by a wet ashing procedure with increased pressure. Powdered biomass (exactly 1 g) was digested in a mixture of HNO_3 and H_2O_2. The ash was then decomposed using a microwave ashing device CEM 2000 (CEM, Matthews, NC) and diluted in aqua regia (nitro-hydrochloric acid). Concentrations of Ca, K, Mg, P, Cu, Fe and Zn were measured by ICP-OES (Thermo Jarrell Ash, Trace Scan, Franklin, NJ). To determine the N concentration, biomass was mineralised in concentrated (98 %) H_2SO_4. Nitrogen concentration was measured by flow colorimetry (SAN plus SYSTEM, Skalar, Breda, The Netherlands). All analyses were performed by an accredited national laboratory, Ekolab Žamberk (www.ekolab.cz).

Fig. 3 Collection of soil samples by M. Gojda (*left*) and by M. Hejcman (*right*) using the soil probe in cropmark number three on 8 June 2012 (photograph by K. Součková)

Data analysis

Factorial ANOVA and one-way ANOVA using the STATISTICA 9.1 program (www.statsoft.com) were used to evaluate soil and plant biomass data. In the case of significant ANOVA results, post-hoc comparisons using the Tukey HSD test were applied, to identify significant differences between cropmarks and controls in both soil layers for each analysed variable. Coding of individual pairs was treated as a random factor in all analyses.

Results

Soil chemical properties

The effect of depth was significant for all analysed soil chemical properties, with the exception of Zn (Table 1). This indicates differences in soil chemical properties between arable and sub-soil layers. With the exception of K, the effect of position (cropmark vs. control) on all soil chemical properties was also significant, which indicates differences in soil chemical properties between controls and cropmarks. With the exception of K and Fe concentrations, the interaction of depth x position was significant for all soil chemical properties analysed, indicating that differences between controls and cropmarks were dependent on the depth of soil sampling. No significant differences for any of the soil chemical properties analysed (organic C, total N, C/N

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Table 1 Results of factorial ANOVA analyses (investigated effects were depth, position (controls vs. cropmarks) and their interaction, *F*F value; *P* probability value obtained by the F test) and investigated soil chemical properties in controls and cropmarks in the upper 0–20 cm arable layer and sub-soil 35–55 cm layer

Chemical property	Depth		Position		Interaction		Mean ± S.E. (n=4)			
	F	*P*	*F*	*P*	*F*	*P*	Control 0–20 cm	Cropmark 0–20 cm	Control 35–55 cm	Cropmark 35–55 cm
C_{org} (gkg^{-1})	27.56	<0.001	69.33	<0.001	51.0	<0.001	12.63±0.74^{a}	13.68±0.8^{a}	1.65±0.52^{b}	15.35±1.29^{a}
N_{tot} (gkg^{-1})	16.72	0.002	50.39	<0.001	23.70	<0.001	1.86±0.07^{a}	2.13±0.09^{a}	0.74±0.04^{b}	2.23±0.22^{a}
C/N	37.98	<0.001	42.45	<0.001	58.22	<0.001	6.79±0.22^{a}	6.42±0.27^{a}	2.13±0.56^{b}	6.91±0.14^{a}
pH ($CaCl_2$)	44.01	<0.001	14.18	0.003	7.51	0.018	7.42±0.05^{a}	7.47±0.06^{a}	7.61±0.06^{a}	7.93±0.01^{b}
Ca (mgkg^{-1})	22.9	<0.001	105.5	<0.001	60.1	<0.001	5305±165^{ab}	7387±960^{b}	2858±897^{a}	17745±988^{c}
K (mgkg^{-1})	21.50	0.001	0.32	0.581	1.26	0.283	221±25.58^{a}	210±16^{a}	112±22^{b}	144±6^{ab}
Mg (mgkg^{-1})	9.33	0.010	79.43	<0.001	46.27	<0.001	99±3.2^{ab}	133±13.56^{b}	40±11^{a}	289±26^{c}
P (mgkg^{-1})	32.8	0.001	242.5	<0.001	189.0	<0.001	512±24.43^{a}	573±48^{a}	242±14^{b}	1229±37^{c}
Cu (mgkg^{-1})	43.47	<0.001	18.30	0.001	16.47	0.002	8.6±0.86^{a}	8.8±0.76^{a}	1.4±0.27^{b}	7.1±0.69^{a}
Fe (mgkg^{-1})	21.32	0.001	11.57	0.005	0.69	0.422	1332±60^{a}	1063±125^{a}	936±149^{a}	493±48^{b}
Zn (mgkg^{-1})	2.1	0.176	204.3	<0.001	134.4	<0.001	13.6±1.29^{a}	16.0±0.89^{a}	1.7±0.35^{b}	25.3±0.85^{c}

Values with the same letter were not significantly different using the Tukey HSD test

ratio, pH ($CaCl_2$), Ca, K, Mg, P, Cu, Fe, and Zn) were recorded between controls and cropmarks in the arable layer (0–20 cm). Values for all analysed soil chemical properties in the sub-soil layer were significantly higher in cropmarks than in controls, except for K, where the increase was not significant.

Biomass properties

Plants of spring barley were approximately twice as tall in cropmarks than in controls and differences were significant (Table 2, Fig. 2b and c). Concentrations of Ca, Mg and P in the aboveground biomass of barley were significantly higher and the concentration of Cu was significantly lower in cropmarks than in controls. The concentrations of N, K and Fe were higher and that of Zn was lower in cropmarks than in controls, but differences were not significant.

Discussion

Soil chemical properties

The main finding of this study is that prehistoric settlement activity can increase soil fertility substantially. Although P fertilizers have either been applied sparingly, or not applied at all, in the Czech Republic over the last 23 years, due to economic reasons (Vaněk et al. 2007; Kunzová and Hejcman 2010), the concentration of plant-available P was very high in all soils analysed. For example, the optimum plant-available (Mehlich III) P concentration in the soil for the nutrition of crops with a high P requirement ranges from approximately 50 to 150 mgkg^{-1} (Strnad et al. 2010; Šrek et al. 2010). In our study, the lowest measured P ranged from 242 mgkg^{-1} in the sub-soil to 512 mgkg^{-1} in the arable layer of controls. In the sub-soil fill of sunken buildings, P availability was extremely high. Although the Mehlich III extraction procedure is routinely used on many agricultural soils in Central Europe (see Semelová et al. 2008; Hrevušová et al. 2009; Černý et al. 2010; Merunková et al. 2012; Pavlů et al. 2012), we recorded P concentrations over 1,000 mgkg^{-1} in the common agricultural soil for the first time. Concentrations of Mehlich III P in common agricultural soils range from approximately 5 to 150 mgkg^{-1} in Bohemia (Matula 2010; Černý et al. 2012; Hejcman et al. 2012; Šrek et al. 2012) and maximum values of soil P recorded in experiments with long-term application of high rates of P fertilizers were about 200–300 mgkg^{-1} (Kulhánek et al. 2009; Kunzová and Hejcman 2009; Hejcman and Kunzová 2010). In addition, the Mehlich III extraction procedure tends to underestimate the concentration of P on Ca-rich soils

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Table 2 Results of one-way ANOVA analyses (*FF* value; *P* probability value obtained by the F test) of biomass chemical properties and plant height in controls and cropmarks

	Position		Mean ± S.E. (n=4)	
	F	*P*	Control	Cropmark
Chemical property				
N (gkg^{-1})	0.792	0.408	17.66 ± 0.92^{a}	19.23 ± 1.48^{a}
Ca (gkg^{-1})	7.042	0.038	4.35 ± 0.26^{a}	6.43 ± 0.74^{b}
K (gkg^{-1})	0.769	0.414	15.3 ± 0.45^{a}	16.53 ± 1.32^{a}
Mg (gkg^{-1})	11.79	0.014	1.1 ± 0.04^{a}	1.43 ± 0.09^{b}
P (gkg^{-1})	6.92	0.045	2.98 ± 0.06^{a}	3.33 ± 0.17^{b}
Cu ($mgkg^{-1}$)	18.15	0.005	17.22 ± 1.69^{a}	8.08 ± 1.32^{b}
Fe ($mgkg^{-1}$)	0.163	0.7	53.52 ± 6.23^{a}	57.5 ± 7.61^{a}
Zn ($mgkg^{-1}$)	0.856	0.391	31.58 ± 3.63^{a}	27.91 ± 1.62^{a}
Height (cm)	251.6	<0.001	36 ± 1.67^{a}	76 ± 1.85^{b}

with a pH above 7.0, like the soil in our study, because of neutralisation of the acidic (pH 2.9) Mehlich III extraction solution (Matula 2010). Therefore, the concentration of P was extremely high in the fill of sunken buildings. This, together with very high concentrations of Ca, Mg, elevated concentrations of Cu and Zn, and the grey colour of the sediment indicates the deposition of highly concentrated biomass ashes (see Hejcman et al. 2011 for the chemical composition of biomass ashes). Similarly, highly increased P, Ca and Mg concentrations extracted by the Mehlich III solution were recorded at sites with wood ash deposition by Novák et al. (2012). It is highly probable that the sunken buildings investigated here served as waste pits after their abandonment and therefore that the settlement existed for some time after the abandonment of the buildings, as the ash from fires in neighbouring buildings was probably used to fill depressions after their abandonment. This can be presumed since there was no known reason to transport the ash over long distances. Very high concentrations of Mehlich III P were also recorded by Hejcman et al. (2011) in the contemporary arable layer of a medieval village abandoned in the thirteenth century. A positive P signature, indicating the presence of ancient settlement, can be therefore recorded in the contemporary arable layer, despite long-term plowing and the passing of hundreds or thousands of years since the abandonment of the settlement (see also Roos and Nolan 2012). In addition to P, markedly high Ca and Mg concentrations as well as high pH values were found in all analysed soils, although sandy soils on silicate sands are typically poor in Ca and Mg and are therefore acidic in the Czech Republic (Kodešová et al. 2011). High Ca and Mg concentrations and pH in the arable layer in comparison to the wider surroundings, if not disturbed by modern activities such as liming, can thus be indicative of abandoned settlements, as was previously reported by Hejcman et al. (2011) on arable land and by Dupouey et al. (2002) in forests. The main sources of Ca and Mg have been biomass ashes, in addition to loam and clay materials used for the construction of houses. The only nutrient with a significantly lower plant-available concentration in the sub-soil of cropmarks compared with controls was Fe. This can be explained by the sub-soil of cropmarks having the highest pH value of all studied soils, because Fe mobility is highly negatively related to soil pH (Hejcman et al. 2009; Vondráčková et al. 2013).

A substantially higher soil organic matter content (organic C and total N) in the sub-soil fill of buildings compared to the sub-soil of controls was shown by the accumulation of organic waste together with the ash. In addition, a large amount of barley roots was recorded in the sub-soil fill of buildings during soil sampling, which contrasted with the almost complete absence of roots in the sub-soil of controls. Decomposed roots also contributed to the presence of more soil organic matter in the sub-soil layer. A higher soil organic matter content in the sub-soil of cropmarks was thus shown by the ancient accumulation of organic waste by humans, together with the improved root growth of modern crops in the fill of sunken buildings. Intensive penetration of crop roots into the nutrient rich sub-soil fill of archaeological features was also recorded in other studies (Hejcman et al. 2011; Gojda and Hejcman 2012). The explanation for this is firstly, the ability of plants to recognise substrates with a high nutrient availability which can then be explored by dense root systems and secondly, the lower mechanical resistance of the fill of archaeological features against the penetration of roots, as was noted during soil sampling.

Biomass properties

Substantially better crop growth in cropmarks above sunken buildings than in controls was shown by improved N, Ca, K, Mg and P nutrition and also by improved water availability to barley plants. Improved P, Ca and Mg nutrition is clearly indicated by a

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significantly higher concentration of these nutrients in the aboveground biomass. Improved N, K and Fe nutrition in cropmarks can be inferred, despite concentrations of N and K being only slightly and non-significantly higher in cropmarks than in controls. This is because an increase in barley plant height of two-fold in cropmarks meant that plants had a lower proportion of nutrient-rich leaves and a higher proportion of nutrient-poor stems in the total aboveground biomass of cropmarks than in controls. This so-called "dilution effect" means that an increase in aboveground standing biomass is associated with a decrease in N, P and K concentration in the total aboveground biomass (Duru and Ducrocq 1997; Hejcman et al. 2010). Therefore, the same concentration of nutrients in the aboveground biomass of tall and short barley plants indicates better nutrition of tall plants. The dilution effect can possibly also explain the lower concentrations of Cu and Zn in the aboveground biomass in cropmarks despite higher plant-available concentrations of Cu and Zn in the soil of cropmarks than in controls. The concentration of nutrients in the total aboveground biomass, even of Cu, Fe or Zn, must therefore be evaluated with respect to plant height or aboveground standing biomass.

Greater water uptake by barley plants in cropmarks than in controls can also be explained by a greater rooting depth of plants in cropmarks and therefore a larger volume of the soil which can be exploited for available water. Furthermore, plants can extract water from deeper soil layers which are generally better supplied by underground water. An increased water supply for plants in positive cropmarks was also measured by Evans and Jones (1977).

Practical implications

Settlement activity substantially increased nutrient availability in the near vicinity of or directly above buildings after their destruction as documented in our study. Thus, former settlement areas, if used as agricultural land, are very fertile and enable extremely high crop production with a concomitantly high nutritive value of agricultural produce as shown in this study. For example, since P is frequently a limiting nutrient for plants, livestock and humans, it is highly desirable to raise plants with high P concentrations (Hejcman et al. 2010). As clearly demonstrated in this study on spring barley, P-enriched agricultural produce can be recorded at sites with ancient settlement activity, even more than 1,000 years after their abandonment (see also Hejcman et al. 2011). Therefore, from the nutrient management point of view, the most efficient scenario for ancient farmers was to build a new wooden building after destruction of the old one (life expectancy was 20–30 years) in the surrounding area and to use the area of the former building and its immediate neighbourhood as a garden, arable field or grassland for forage production. This principle can explain why so many buildings and a very high nutrient availability can be recorded in prehistoric settlements, since buildings were constructed and used by generations of farmers who transported large amounts of nutrients from the landscape into settlements. It appears that prehistoric farmers often moved their houses within the area of settlement and used soils enriched by their ancestors for crop production.

Conclusions

1) Prehistoric settlement activity substantially increased nutrient availability in the former settlement area. The most conspicuous differences were high soil pH and plant-available concentrations of P, Ca, Mg, Cu and Zn in the sub-soil fill of former sunken buildings in comparison to sub-soil of controls. High soil pH and concentrations of P, Ca and Mg were also found in the surrounding area of prehistoric buildings in the contemporary arable layer. We conclude that the chemical signature of prehistoric settlement activity can be detected using both the chemical analysis of the sub-soil layer and the analysis of the contemporary arable layer.
2) The doubling in barley plant height in positive cropmarks above prehistoric sunken buildings can be at least partly explained by improved crop nutrition in comparison to controls, particularly with respect to N, P, K, Ca and Mg. Prehistoric settlement activity can thus positively affect production of contemporary crops in Central Europe.

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