

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: <http://www.elsevier.com/locate/jas>

Cropmarks in main field crops enable the identification of a wide spectrum of buried features on archaeological sites in Central Europe

Martin Gojda ^{a,b}, Michal Hejcman ^{c,d,*}

^a Department of Archaeology, University of West Bohemia, Sedláčkova 15, 306 14 Plzeň, Czech Republic

^b Institute of Archaeology, Czech Academy of Sciences, Letenská 4, 118 01 Prague 1, Czech Republic

^c Department of Ecology, Faculty of Environmental Sciences, Czech University of Life Sciences, Kamýčká 129, CZ-165 21 Prague 6, Suchdol, Czech Republic

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

ARTICLE INFO

Article history:

Received 5 March 2011

Received in revised form

17 January 2012

Accepted 19 January 2012

Keywords:

Aerial prospection

Barley and wheat

Cropmarks

Plant nutrition

Rape

Remote sensing

ABSTRACT

Buried (syn. sunken, sub-surface and sub-soil) archaeological features on arable land can frequently be discovered due to visually detectable changes in crop growth termed cropmarks. The aim of this paper was to demonstrate the range of features identified through cropmarks on aerial photographs in stands of main field crops in the Czech Republic.

Low-altitude oblique aerial photographs of cropmarks were collected from an aircraft from a height of 300–500 m above ground during approximately 800 flight hours from 1992 to 2010. Some features discovered via cropmarks were excavated by standard archaeological methods.

Around one thousand cropmarked sites were discovered. The highest density of archaeological sites was on sandy soils in dry lowland regions, and a substantially lower number on loess or clay soils or in regions above 350 m a.s.l. Cropmarks were best developed in barley (*Hordeum vulgare*), followed by wheat (*Triticum aestivum*), winter rape (*Brassica napus*) and lucerne (*Medicago sativa*). The most common archaeological sites discovered via positive cropmarks were ancient funeral and settlement areas, with many related features such as waste pits, sunken dwellings, post holes, ditches and graves. Abandoned roads were the most commonly negatively cropmarked features. Positive cropmarks represented 98% and negative only 2% of all recorded cropmarks.

Archaeological features present beneath the modern arable horizon can irreversibly change sub-soil properties and growth of crops. Arable fields in Czech lowlands represent a unique archive of buried archaeological features, recording human activities in the landscape over the last 7500 years.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

In the agricultural landscape of many countries, archaeological features are most frequently buried under a modern arable layer and can be identified through different sub-soil chemical and physical properties. Chemical analysis of the modern arable layer cannot be used for their identification as decades of deep ploughing has levelled the small scale variability in arable layer properties induced by ancient human activities. Plants are able to take up scarce water and nutrients from sub-soil layers, therefore buried (syn. sunken, sub-surface and sub-soil) archaeological features can frequently be discovered due to visually detectable changes in crop

growth, termed cropmarks, which are well detectable on aerial photographs (Evans and Jones, 1977; Stanjek and Fassbinder, 1995; Bewley and Raczkowski, 2002; Gojda, 2006; Trier et al., 2009; Cowley et al., 2010).

Field crops can distinctly indicate sub-soil archaeological features, because their rooting depth frequently exceeds the thickness of the arable layer. In winter wheat (*Triticum aestivum* L.) for example, the majority of their roots are located in the arable layer up to the upper 30 cm, but their maximal rooting depth can exceed 2 m (Canadell et al., 1996; Kirkegaard and Lilley, 2007). Penetration of roots into deep sub-soil layers is highly affected by soil porosity (White and Kirkegaard, 2010), by the mechanical resistance of soil to root penetration (Kirkegaard et al., 2007) and by water and nutrient availability at particular soil depths (Haberle et al., 2006).

Positive cropmarks with extraordinary high biomass production of crops can be recorded above buried waste pits, sunken dwellings, graves and ditches filled by nutrient rich sediments with high

* Corresponding author. Department of Ecology, Faculty of Environmental Sciences, Czech University of Life Sciences, Kamýčká 129, CZ-165 21 Prague 6, Suchdol, Czech Republic.

E-mail address: hejcman@fzp.czu.cz (M. Hejcman).

porosity and low mechanical resistance, enabling plants to produce deep roots and improving their water and nutrients supply (Hejzman and Smrž, 2010). In addition to the increase in biomass production, positive cropmarks can be identified according to delays in crop ripening, higher concentrations of growth limiting nutrients in the plant biomass (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in particular) and therefore resulting in different colours of stands, an increase in plant height, crop density, more frequent lodging and different shapes and size of crop plants growing above buried archaeological features compared to plants growing in control areas with undisturbed sub-soil (Majer, 1996; Hejzman et al., 2011). Negative cropmarks with markedly reduced crop growth and early crop ripening can be recorded above ancient roads with highly compacted sub-soil layers, and above wall foundations that negative affecting the water and nutrient supply of the crop (Doneus, 2001; Hanson and Oltean, 2003; Lasaponara and Masini, 2007).

The contrast between cropmarks and control surrounding stands are most pronounced in cereals (Evans and Jones, 1977; Gallo et al., 2009), but can also occur in stands of lucerne (*Medicago sativa* L.), maize (*Zea mays* L.), pea (*Pisum sativum* L.), sun-flower (*Helianthus annuus* L.), winter rape (*Brassica napus* L.) and sometimes in stands of root crops (Gajda, 2005; Hejzman and Smrž, 2010). In addition to the different effect of crop species, cropmark formation is to some extent dependent on geological substratum, soil quality, depth of the buried features beneath the arable layer as well as on weather conditions. The best developed cropmarks are generally recorded on shallow sandy soils with low nutrient availability and during dry years (Evans and Jones, 1977; Challis et al., 2009).

Although cropmarks and their use for the detection of archaeological features by means of archaeological remote sensing (ARS) have been used in the UK since the 1920s (Crawford, 1924), it was not until the fall of the Iron Curtain in 1989 that their use began to evoke more widespread interest across the whole of Europe (Hašek and Kovárník, 1999). Therefore little is known about the density and spectrum of archaeological features detected via cropmarks in the post-communist countries of Central Europe. The aim of this paper was therefore to demonstrate: (1) the range and density of buried archaeological features that were identified via cropmarks, and (2) to demonstrate the value of different field crops for ARS in Bohemia, in the western part of the Czech Republic, where ARS started in 1992.

2. Materials and methods

2.1. Study area

Bohemia belongs to just a few European regions in which ARS (most extensively by means of low altitude aerial reconnaissance) has been extensively and continuously applied for a long period. In this study we examine the results obtained by the Institute of Archaeology of the Czech Academy of Sciences between the years 1992 and 2010. Since its inception in 1992, the survey has concentrated on lowland areas of broad valleys of the middle and lower streams of major Bohemian watercourses with well developed Pleistocene terraces: the Moldau (Vltava in Czech), Elbe (Labe), Eger (Ohře) and Isara (Jizera) rivers and their tributaries, the Cidlina and Mrlina rivers, including local valley streams (see Fig. 1, polygon 1). Due to favourable environmental conditions, this area is known as the most fertile part of Bohemia and has always formed the core of Czech territory that has been continuously occupied by prehistoric, medieval and post-medieval populations (Gajda, 2004). This area is characterised by low mean annual precipitation (450–550 mm) and high mean annual temperature (8–9 °C), in the context of Central Europe.

Within the framework of this large territory, one of the most frequently air surveyed areas has been the landscape around the Říp Mt. (Fig. 1, polygon 1, area A; Fig. 2), a solitary mountain situated on the border between central and north-western Bohemia, whose history is connected with the legendary arrival of the Slavs into Bohemia in the 6th century AD. During the years 2005–2010, the territory around Říp Mt. was explored intensively in a project by the University of West Bohemia (Gajda and Trefný, 2011). Most of the photographs presented in this article were taken then. The core of the study area covers approximately 100 km².

In southern Bohemia (polygons 2, 3, 4 on Fig. 1), the survey was carried out systematically between 1997 and 2002 (a joint project of the Institute of Archaeology in Prague and Museum of South Bohemia in České Budějovice, aimed at the comparison of the potential of ARS when applied in lowland and in higher altitudes). This area is characterised by almost no light sandy soils developed on sandy and gravel substrates, a higher annual precipitation (600–700 mm) and lower annual temperature (7–8 °C) than in polygon 1.

2.2. Data collection

Flights were performed between April and August, with approximately 800 flight hours. Low-altitude oblique aerial photographs of cropmarks were collected from a Cessna 172 aircraft from a height of 300–500 m above ground. During the collection of photographs, the speed of the aircraft was usually 140–160 km per hour. At the start of the growing season, aerial surveys were performed from early morning to late afternoon. In June, July and August, when the height of the crop increased and the crop height differed markedly between the cropmarks and the surrounding vegetation, aerial surveys were performed in the morning and in the late afternoon when the sun was low above the horizon and the differences in crop heights were the most obvious. Surveys were preferentially carried out on sunny days with no wind. Concerning the case study area around Říp Mt. (Fig. 2), individual localities were visited after processing the aerial photographs of cropmarks, and crops were recorded.

Identified features on archaeological sites were classified according to Table 1 and marked on maps (1:10,000 and 1:50,000). In the majority of cases, the dating of archaeological features at the discovered sites was based on pottery fragments collected by means of plough-walking and surface artefact collection. Some of the discovered sites were also test excavated and/or measured by magnetometry. A few features could be dated due to their morphology, but some localities remained undated as no datable pottery was collected during ground fieldwork.

2.3. Data evaluation and presentation

As the research was based on the collection of aerial and ground collected photographs, no “hard” biological or chemical data were collected and therefore no statistical evaluation was used within the paper. The suitability of the most frequently planted crop species for identification of sub-soil archaeological features was demonstrated according to photographs and long-term personal experiences of the authors, as no other exact method was available. The photographs used in this paper were selected to present: (1) the scale of cropmarked archaeological features discovered in the study area, and (2) the value of different crops for ARS. Furthermore, in order to demonstrate how well field crops can indicate human-induced changes in sub-soil layers, we selected aerial photographs of cropmarks which were after their discovery excavated by standard archaeological field methods.

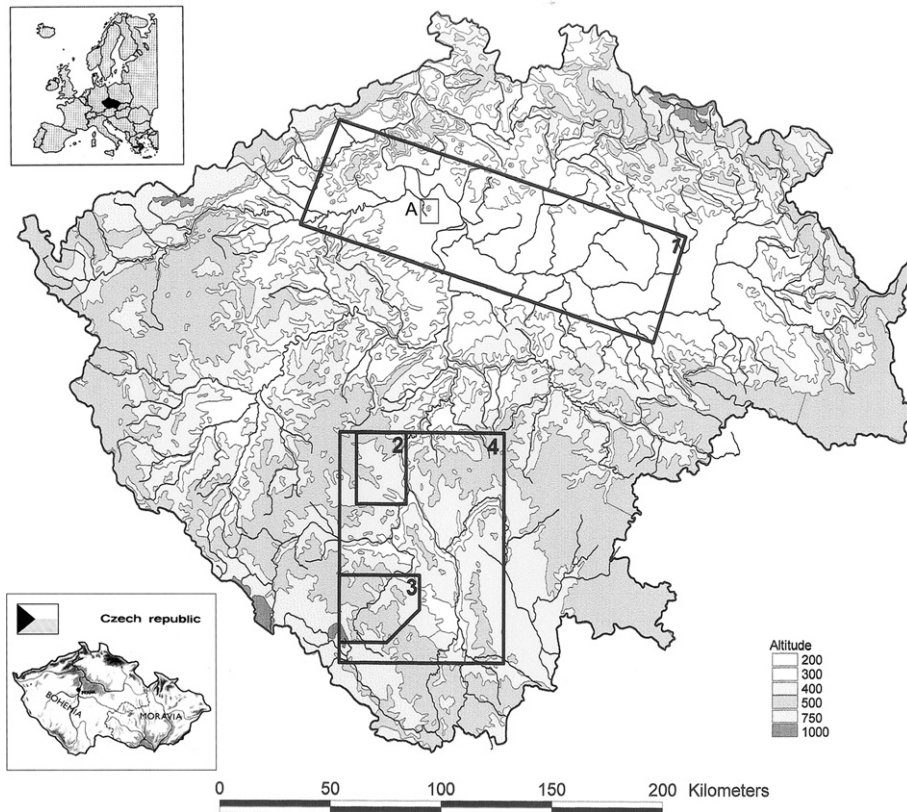


Fig. 1. Bohemia (Western part of the Czech Republic): areas of the most intensive archaeological air survey. Most of the cropparked prehistoric sites with buried archaeological features have been identified in polygon No. 1 (basins of Elbe, Isara, Cidlina, lower Moldau and mid-central Eger rivers). A – the Říp Mt. area corresponding to the map in Fig. 2. Polygons 2, 3 and 4 indicate highly surveyed areas in southern Bohemia around the middle Moldau river.

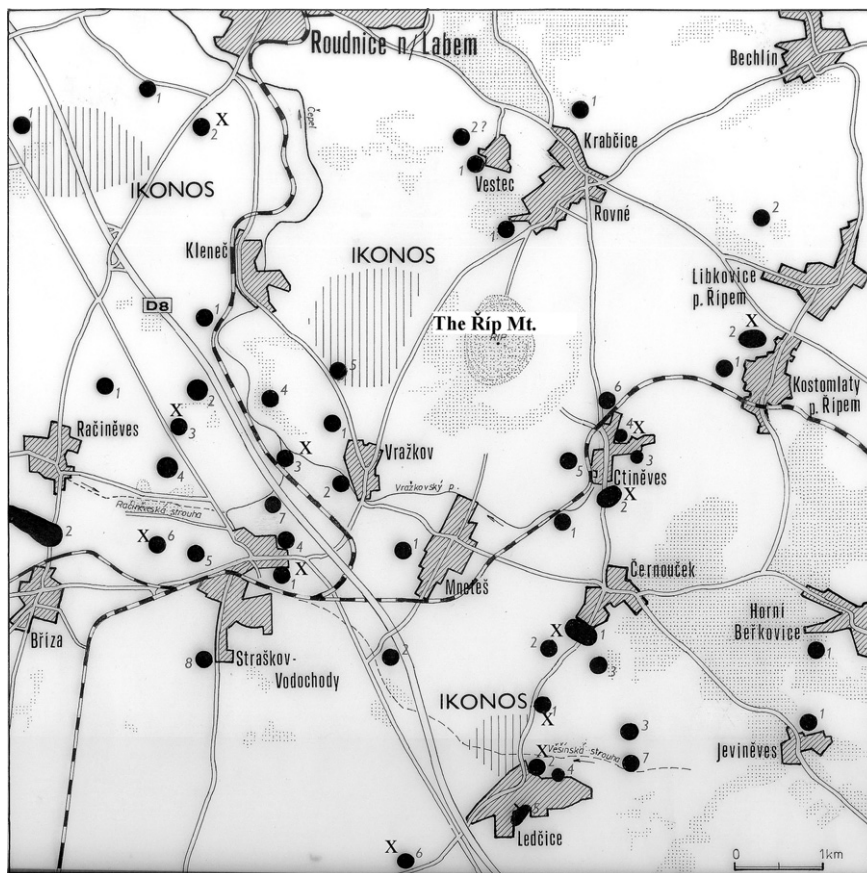


Fig. 2. The Říp Mt. area with indications of prehistoric settlement areas (black points) visualised via cropparks and identified during aerial prospection performed from 1992 to 2010. The sites are numbered separately for the cadastre of each contemporary settlements; x – areas identified during aerial reconnaissance and also identified in the Google Earth application; hatched areas with IKONOS label: areas including linear systems detected by IKONOS satellite imagery. Names in the map indicate contemporary villages.

3. Results

3.1. Summary of main results

Since the beginning of the aerial prospection in 1992 up until 2010, aerial survey campaigns over selected parts of Bohemia revealed around one thousand of cropmarked archaeological sites. The highest density of archaeological sites (approximately one site per 3 km²) was recorded on sandy soils in dry lowland regions, and a substantially lower density was recorded on loess or clay soils or in regions with altitudes above 350 m a.s.l. (approximately one site per 7 km²). Approximately 90% of all cropmarked localities have been identified in the northern half of Bohemia (polygon 1 on Fig. 1) and the remaining 10% in southern Bohemia (polygons 2, 3, 4 on Fig. 1). A high density of cropmarked archaeological sites with many features was discovered, especially in the Mt. Říp area (one site per 2.5 km², Fig. 2). Ninety-eight percent of discovered archaeological features were indicated by positive cropmarks, and only two percent were indicated by negative cropmarks.

3.2. Archaeological sites and features indicated by positive cropmarks

The most common archaeological sites discovered via positive cropmarks were ancient settlement areas from Neolithic (5500–3500 BC) up to early Middle Ages (600–1200 AD, Fig. 3) with many related individual archaeological features, such as settlement or waste pits, sunken dwellings or post holes. The number of small archaeological features in individual settlement areas ranged from several up to hundreds in the case of large settlements.

Funerary areas with burials enclosed by circular ditches filled by humus rich sediment, which are dated to the period between late Eneolithic (2800–2200 BC) through to the end of the early Iron Age (600–500 BC) were the second most common category of archaeological localities indicated by positive cropmarks (Figs. 4, 5, 7c,d and 8). Rectangular ditches had been most frequently used in the transition period between the early and late Iron Ages. The third group of discovered archaeological features represented defensive or ritual enclosures protecting settlements or ritual areas (Figs. 6 and 7a,b).

The effect of soil substratum on the creation of cropmarks is visible in Fig. 6a and b. Double ditches, sunken dwellings and settlement pits were clearly indicated by well developed positive cropmarks in the stand of winter wheat in a moderately elevated area with a higher proportion of sand in the soil and lower depth of humus horizon because of erosion, than in the lower elevated neighbourhood with soil accumulation and therefore deeper humus layer with higher proportion of clay. In lower elevated area, there were no, or only negligible, cropmarks above archaeological features covered by a deep humus rich layer.

3.3. Archaeological sites and features indicated by negative cropmarks

Abandoned roads were the most commonly negatively cropmarked archaeological features recorded in the study area. In a few cases, the position of individual trees around ancient roads were identified, such as in the case of a site documented by an oblique aerial photograph in Fig. 6c. Positions of former trees were indicated by positive point cropmarks in winter wheat stand, and verified according to historical military maps from the 1830s (Fig. 6d). Negative cropmarks indicating stone walls or fundamentals of buildings were discovered only rarely.

3.4. Effect of crop species on the development of cropmarks

Cropmarks were the best developed in the stands of cereals, in particular in winter or summer barley (*Hordeum vulgare* L.). The high suitability of winter barley for the identification of archaeological features is obvious from Fig. 3b. Delay in ripening of barley above buried archaeological features was well detectable according to the dark green colour of the crop on aerial photographs. Variability in colours of barley thus enabled precise mapping of the prehistoric settlement area. In the same area, many archaeological features were recorded as well as in the stand of lucerne in different years (Fig. 3a), but the resolution of cropmarks was not as good as in the case of barley. Cropmarks in lucerne stands were the best developed during the dry summer months when other crops were harvested.

Positive cropmarks in stands of winter barley enabled the identification and precise mapping of a unique Eneolithic enclosure on the sandy terrace of the Elbe River. In this enclosure, the dark green colour of barley above ancient ditches filled with humus rich soil (see Fig. 7b) well contrasted with the yellow barley in their neighbourhood. Similarly the green colour of barley enabled the identification of a palisade trench parallel to the ditches on the inner side of the enclosure.

In addition to colour changes, barley responded to the presence of sub-soil archaeological features by conspicuous changes in crop height. For example, spring barley was from 10 to 20 cm higher above buried archaeological features in ancient residential areas than in the neighbourhood with undisturbed sub-soil horizons (see Fig. 3c). Higher spike density and spike size of winter barley (Fig. 7c) above a shallow trench filled with humus rich soil (Fig. 7d) enabled the identification and mapping of middle Bronze Age to early Iron Age (1500–500 BC) funerary areas.

Winter wheat was the second most suitable crop for the identification of buried archaeological features in the study area. Cropmarks in stands of winter wheat enabled the identification of small scale as well as large-scale archaeological features (see Figs. 4a,c, 5a, 6a,b and c), although cropmarks were not as conspicuous as in the case of winter barley.

Cropmarks in winter rape were well developed, especially in the developmental stage of flowering. The most conspicuous was the logging and delay of rape flowering above buried archaeological features which improved plant nutrition (Fig. 4b). In other cases after flowering, buried features such as waste pits, graves or ditches were well indicated by the higher standing biomass of rape than in the neighbourhood (Fig. 5b), or by the dark green colour of the stands (Fig. 3d).

















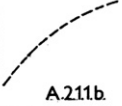
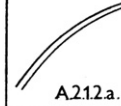
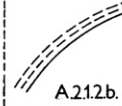
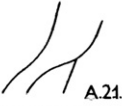
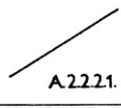
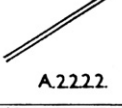
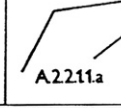
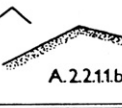


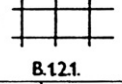
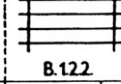









3.5. Effect of ancient human activities on content of sub-soil organic matter

As evidenced by the dark colour of sediments in buried features in comparison with the control undisturbed sub-soil layers (see archaeological excavations in Figs. 4d, 5d, 7b,d, 8a and b), many ancient human activities increased the content of soil organic matter in the sub-soil, and this increase was irreversible.

4. Discussion

Although modern agronomy and ARS seem to be absolutely unrelated scientific disciplines, they are highly connected through the investigation of human-induced variability in field crops production termed cropmarks. This variability, very visible on oblique aerial photographs, enabled the discovery and documentation of thousands of archaeological features buried under the modern arable layer in the agricultural landscape of the Czech

Table 1
The morphology of buried features (in non-equivalent scale) as identified by air survey in Bohemia since 1992 (according to Gojda, 2004).

Group	LINEAR FEATURES (lines and enclosures) and MACULAE								
A.1.1.	 A.111.1	 A.111.2	 A.112.1	 A.112.2	 A.112.3	 A.112.4	 A.113		
A.1.2.	 A.121.1	 A.121.2	 A.122.1			 A.122.2	 A.122.3a	 A.122.3b	
A.1.3.									
A.2.1.	 A.211a	 A.211b	 A.212a	 A.212b	 A.213				
A.2.2.	 A.222.1	 A.222.2	 A.221a		 A.221b		 A.2212		
B.	 B.11		 B.12.1		 B.12.2				
C.	 C.11	 C.12.1	 C.12.2	 C.2					
I.-III.	 I	 II.1	 II.2		 III.1	 III.2			

Republic. A high density of cropmarked archaeological features was recorded, especially in lowlands at altitudes up to 350 m a.s.l. because these areas had been densely inhabited since Neolithic times and there were better environmental conditions for development of cropmarks than at higher altitudes (see also Hejcman and Smrž (2010) for results from other parts of Bohemia). In the Říp Mt. area for example, the production of modern crops has been positively affected by former human activities on almost an every arable field. Every farmer thus had the possibility to see positive effects of prehistoric settlement activities on the production of modern crops. Czech lowlands, in contrast to higher altitudes, frequently suffer from moisture shortage during the vegetation season (Trnka et al., 2008; Hlavinka et al., 2009) and the extremely dry spring such as those in 2000 and 2003 were the best for the creation of extremely visible cropmarks. Many new archaeological sites or individual features which had previously not been discovered were identified during those springs. The extraordinary creation of cropmarks in dry years was consistent with results from other European countries (Cowley, 2002; Kershaw, 2003; Hanson and Oltean, 2003; Challis et al., 2009). The highest density of archaeological features discovered on sandy and sandy-gravel river terraces was because people in prehistory preferred to live in close vicinity to water sources, as evidenced by permanent archaeological investigations (see Gojda, 2004; Kuna, 2007).

Arable fields in the Czech lowlands represent a unique archive of buried archaeological features, recording human activities in the landscape over the last 7500 years. Buried archaeological features such as graves, trenches, sunken buildings and waste pits can be well identified and documented according to positive cropmarks in

stands of main field crops, particularly in spring and winter barley, winter wheat, winter rape and lucerne. The high suitability of barley and wheat for the identification of buried archaeological features is because of their high colour and height response to a decrease or increase in water and nutrient supply, as evidenced by long-term fertiliser experiments in the Czech Republic (see Kunzová and Hejcman, 2009, 2010; Černý et al., 2010; Hejcman and Kunzová, 2010). The excellent value of barley for the identification of archaeological sites is consistent with results by Hejcman and Smrž (2010) from the Czech Republic, or with results by Agapiou and Hadjimitsis (2011) from Cyprus. Barley is very sensitive to drought stress which can be alleviated by improved N nutrition (Krček et al., 2008), which has been recorded above buried archaeological features (Hejcman et al., 2011).

With the exception of former roads and several later (post-medieval) buildings, almost all archaeological features discovered were positively cropmarked. This is because wooden dwellings were constructed in prehistory with a minimal use of stones in the study area. Stone buildings have been constructed since the 13th century when the structure of contemporary settlements was established in the Czech Republic, thus ruins of stone buildings cannot be recorded in the sub-soil of contemporary arable fields. This highly contrasts with areas of the former Roman Empire, and Provinces where stone buildings were frequently constructed and therefore negative cropmarks on field crops can be recorded more frequently (see Evans and Jones, 1977; Doneus, 2001; Hanson and Oltean, 2003; Fassbinder, 2010; Verhoeven and Schmitt, 2010).

In many cases, archaeological sites represent unique “unintended” fertiliser experiments.

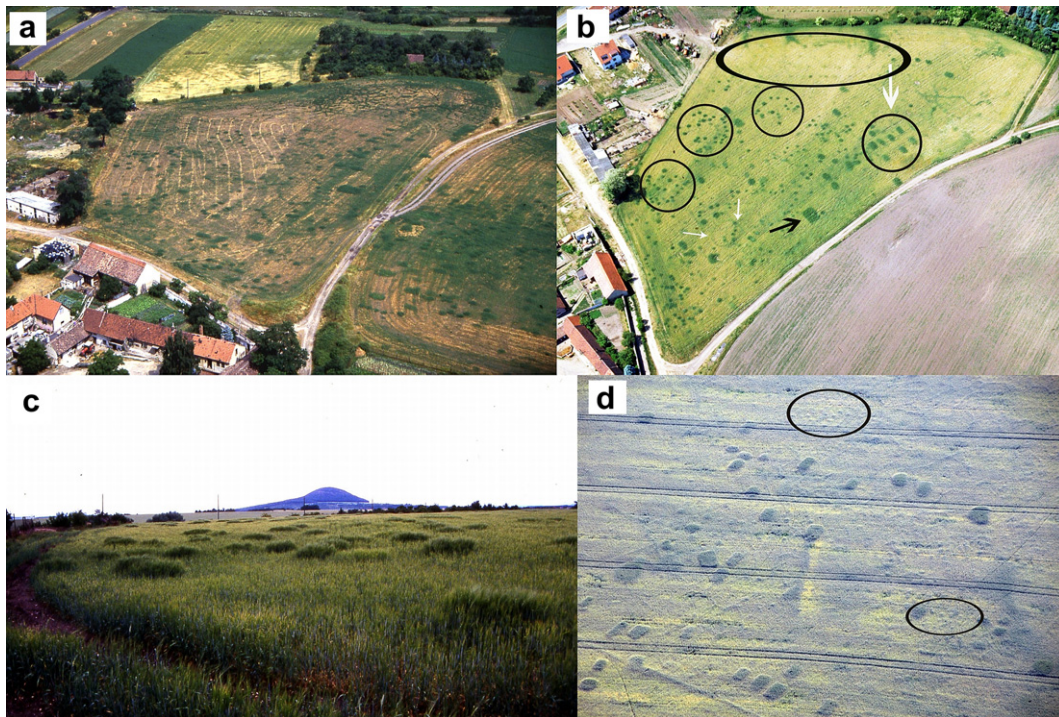


Fig. 3. Part of a prehistoric settlement area probably used from Eneolithic to the La Tène period, close to the contemporary village of Ledčice (see Fig. 2). (a) Positive cropmarks in the stand of lucerne photographed on 8 July 1994. (b) The same area with winter barley photographed on 1 June 1999. Positive cropmarks in circles indicate sub-soil archeological features probably of the same age because of their regular spatial arrangement. In the black ellipse in the upper part of the photograph, a system of point features arranged in rows enabled the identification of the position of individual trees in a former orchard. The big white arrow indicates a cluster of point cropmarks, probably documenting graves or small sunken buildings. Two small white arrows indicate the position of a small circular enclosure. The black arrow indicates cropmarks above sub-soil sunken buildings. (c) Ground photograph of the positive cropmarks in the multicultural prehistoric settlement area taken on 15 June 1997. Spring barley was substantially higher above sub-soil archeological features. "Říp" – Sacred Mountain for all Czechs is in the background of the photograph (see map in Fig. 2). (d) Clearly visible are positive cropmarks above sunken buildings in the stand of winter rape close to the contemporary village of Račíněves, photographed on 23 May 2009 (see map in Fig. 2 for location). Black circles indicate regularly arranged small-scale positive cropmarks showing the position of sub-soil post holes in the construction of large above ground buildings.

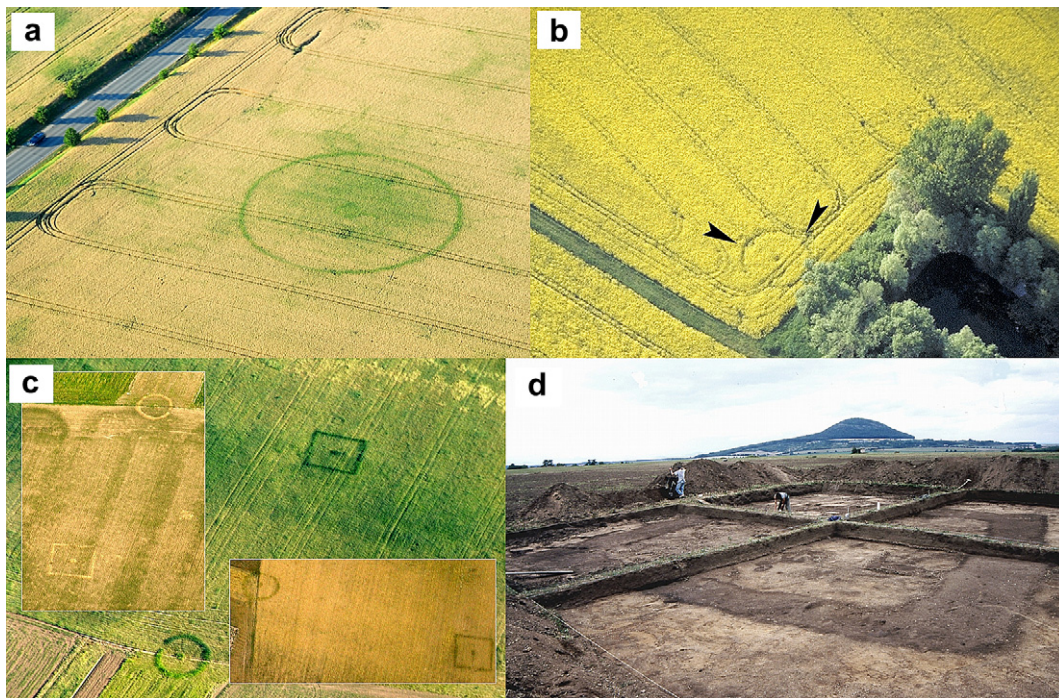


Fig. 4. Funeral areas identified through positive cropmarks. (a) Prehistoric ring ditch with central *macula* (grave pit) in a stand of winter wheat photographed on 3 July 2010; (b) the same (although smaller in diameter) type of archaeological feature identified through cropmarks in flowering winter rape (25 May 2000); (c) Rectangular and circular ditches (enclosures) with central points (*maculae*) from the early La Tène period (500–600 BC) photographed in stands of winter wheat in different phenological stages, close to the contemporary village of Černouček (see map in Fig. 2) between 1997 and 2007; (d) Archaeological excavation of rectangular enclosure from (c) performed between September–October 1997.



Fig. 5. Late Bronze Age settlement area with waste pits visible as hundreds of points, and a grave (? – the excavation had not been finished in 2010) pit surrounded by a double rectangular ditch (indicated by arrow) in the contemporary village of Ctineves (see map in Fig. 2 for location). Waste pits, grave (?) and ditches were identified through positive cropmarks in (a) winter wheat stand photographed on 30 June 2007, and (b) in winter rape photographed on 23 June 2006. (c) Aerial photograph of archaeological excavation of the grave (?) pit and ditch (28 August 2009); (d) Infill layers rich in humus inside the grave (?) pit highly contrasted with yellow sandy sub-soil of the undisturbed sub-soil in the neighbourhood. The photograph was taken on 13 July 2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Positive cropmarks above graves can be connected with the improved nutrition of a crop. Graves can irreversibly change soil P status (Erneé and Majer, 2009) and can irreversibly improve P nutrition. This is because the amount of P in one human body, depending on live weight, is approximately 0.5–0.8 kg (Mitchell et al., 1945) and the area of the grave is up to 2 m². In many cases, depending on soil reaction and water regime, even P from bones can be taken up by plants as bones can be dissolved in the soil over hundreds or thousands of years (see Fig. 8, Nielsen-Marsh and Hedges, 2000). Furthermore, in addition to skeletal graves, cremation was used in many cultures from the middle Bronze Ages up to Early Middle Ages (Sorensen and Rebay-Salisbury, 2008), and human and wood ash is very rich in P (Holliday and Gartner, 2007). In graves, the application rate of P can be at least 2500–4000 kg P ha⁻¹ which is one hundred times higher than the normal annual P application rates for main field crops in Central Europe (see Černý et al., 2010; Kuzová and Hejzman, 2010; Šíp et al., 2009; Šrek et al., 2010). Taking into account the low mobility of soil P and the ability of crops to explore sub-soil layers for scarce nutrients (Haberle et al., 2006), positive cropmarks due to improved P nutrition of crops above graves can be irreversible. In addition to P, improved N nutrition and water supply can be recorded above graves. The amount of N in one human body is 1.2–2 kg (Mitchell et al., 1945) and this is an application of 6000–10000 kg N ha⁻¹ which is one hundred times higher than the normal annual N application rates for cereals in the Czech Republic (Nedvěd et al., 2008; Hejzman and Kunzová, 2010). Although the mineral N is highly mobile in the soil profile and can be quickly leached (Pavlík et al., 2010), some part of N can be incorporated into the soil organic matter which can survive in the soil for thousands of years (see Fig. 8; Dupouey et al., 2002;

Dambrine et al., 2007). Positive cropmarks above graves can be therefore explained by the high content of soil organic matter in graves, and the positive effect of high P availability on N mineralisation and therefore on N nutrition of the plants together with their improved water supply due to deeper rooting and the higher water holding capacity of humus rich soil. Furthermore, the location of nutrient rich sediments in the sub-soil forces plants to create a higher proportion of deep roots as they can easily penetrate the humus rich infill of archaeological features and explore them for growth limiting nutrients and water. During the excavation of the grave in Fig. 5d, for example, roots of winter wheat were recorded at a depth of 2.5 m from the surface, although no roots were recorded in the undisturbed and highly compressed sandy sub-soil in the surroundings of the grave. This is in accordance with the conclusion of Kirkegaard et al. (2007) that the penetration of roots into deep layers is highly affected by the mechanical resistance of soil to root penetration.

Positive cropmarks above ditches were produced by the improved plant water and nutrients supply because of the substantially deeper humus rich layer than the thickness of the arable layer. In the Czech Republic, the thickness of the humus rich arable layer is normally 20–30 cm, and the humus rich infill of ditches, normally ancient arable soil from the surroundings mixed with nutrient rich wastes, can be over 2 m in the case of military or ritual fortifications (Hašek and Kovárník, 1999; Krivánek, 2006). This enables plants to create deep roots and to take up higher amounts of water and nutrients from the humus rich infill of ditches than from the undisturbed sub-soil in the surrounding.

Positive cropmarks above sunken dwellings and waste pits were produced by an improved plant water and nutrient supply because of their humus rich infill, the most frequently ancient humus rich



Fig. 6. Part of prehistoric settlement area with waste pits and sunken buildings surrounded by double ditch (indicated by arrows) in the stand of (a) flowering winter wheat photographed on 1 May 2007 and (b) in fully ripe stand photographed 30 June 2007. Positive cropmarks were very visible in areas with shallow sandy soil but substantially worse in area with deeper soil with higher clay and silt proportion. (c) Regularly distributed dark green points (*maculae*) and a light line in stand of winter wheat indicating a former trackway lined with trees near the village of Rybnany (NW Bohemia), as evidenced (d) on a map from the 1830s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

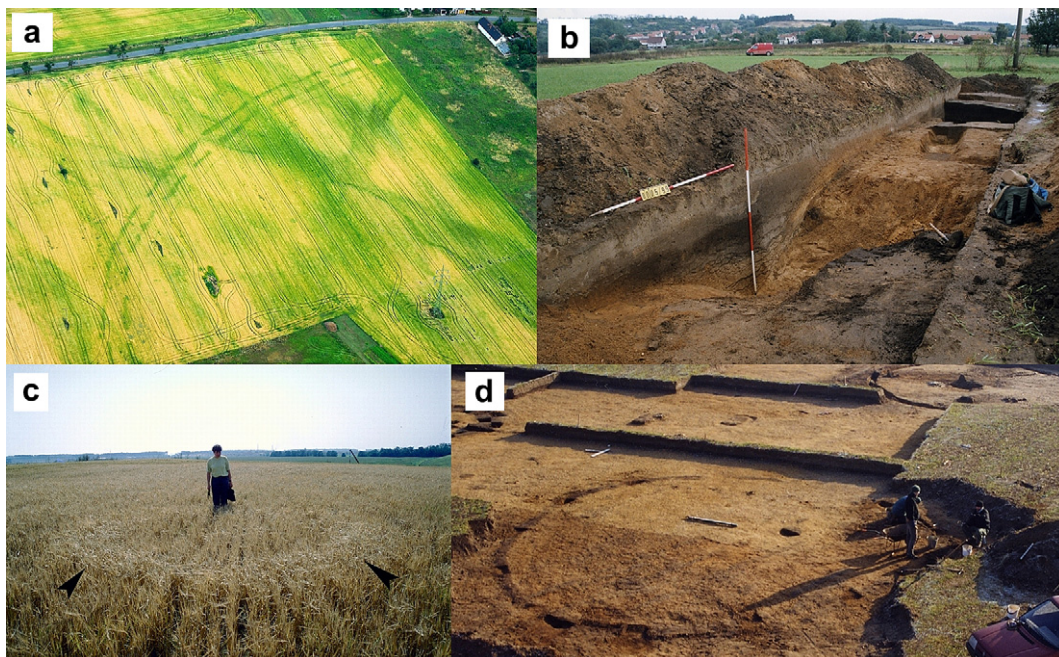


Fig. 7. (a) Positive cropmarks in winter barley enabled the detection of a double interrupted ditch and palisade trench of an Early Eneolithic Michelsberg culture (4000 BC) enclosure. Photograph was taken on 1 July 2010. (b) Excavation of the enclosure performed in 1999. Ditches were filled by humus rich sediments and undisturbed sub-soil was sandy. (c) Positive cropmarks in winter barley indicate a funeral area from the Bronze Age surrounded by a ditch (early July 1994); (d) The same area during archaeological excavation in 1999.

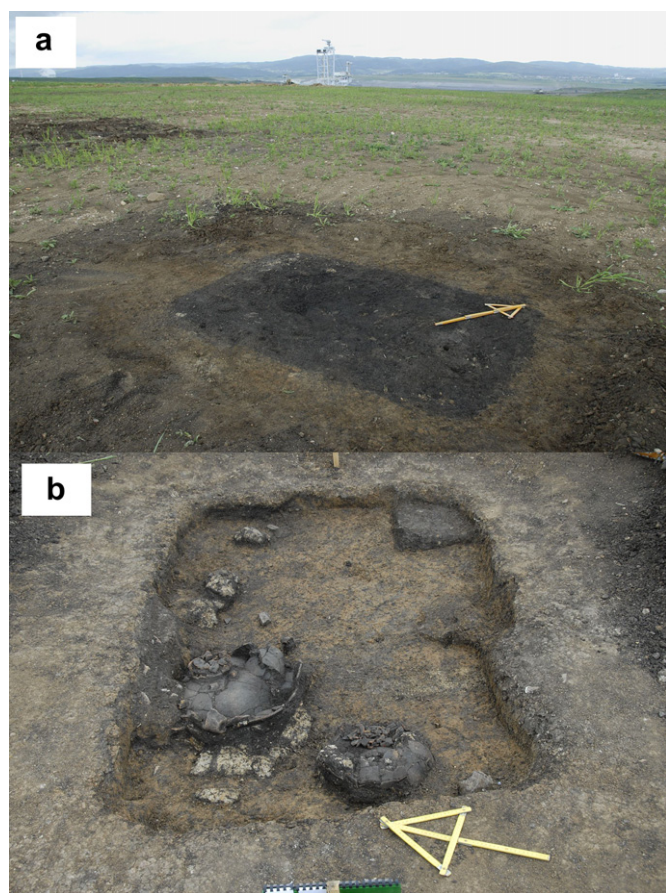


Fig. 8. Archaeological excavation of sub-soil Eneolithic grave (2700 BC) performed by Dr. Z. Smrží in NW Bohemia in the summer of 2009. After removal of the arable layer, (a) black humus rich infill of the grave highly contrasted with lighter sub-soil in the surrounding. (b) Skeleton was completely dissolved and the position of the former body was indicated only by the position of pottery vessels.

upper soil from their surroundings. Furthermore, waste pits were frequently filled with wood ash which can irreversibly, substantially increase P, K, Ca, Mg and Zn soil status and therefore plant nutrition (Semelová et al., 2008). The amount of wood ash deposited in waste pits is generally very high, thousands of tons per hectare. Taking into account the mean concentrations of nutrients in wood ash (Augusto et al., 2008), the amount of P, K, Ca and Mg deposited in waste pits is higher than 10 t of each nutrient per hectare! Such a huge amount of nutrients can hardly be taken up by plants even over thousands of years (see Hejzman et al., 2011).

The higher biomass production of crops can be identified, even above post holes with an area of only several square decimetres and with depths of up to 40 cm below the arable layer. On sandy soils, post holes can be identified as a positive small scale cropmarks, thousands of years after the wooden houses' destruction. Post holes are filled with humus rich sediment from the decomposed wood. The mapping of such small scale positive cropmarks in stands of cereals, in particular barley, enables the ground plans of prehistoric houses to be reconstructed with high precision, even without any archaeological excavation. Therefore any human activity disturbing sub-soil layers can generate irreversible changes in the productivity of arable fields.

Since there has been no or scarce communication between agronomists and archaeologists in the Czech Republic, cropmarks and their high value for archaeology are generally not known to farmers. According to our experience, farmers frequently believe

that cropmarks are rather an indication of the uneven application of fertilisers and other agrochemicals than the presence of buried archaeological features. Cropmarks indication of the uneven application of agrochemicals can be easily distinguished from cropmark indications of buried archaeological features because of their temporal character and different shapes.

5. Conclusion

As presented in this study, a major part of the variability in modern field crop production can be as a result of variability in sub-soil layers. Buried archaeological features present beneath the modern arable horizon can substantially and irreversibly change the biomass production of field crops. In the Czech lowlands, buried archaeological features such as sunken dwellings, enclosures, ditches, waste pits and graves, can be well identified on sandy soils according to cropmarks in stands of main field crops, in particular barley, wheat, rape and lucerne.

Acknowledgement

The anonymous reviewers are gratefully acknowledged for their useful comments. M.H. gratefully acknowledges the financial support provided by the Czech Science Foundation (project GACR 521/08/1131), and M.G. for the support of the Academy of Sciences of the Czech Republic (research project AV0Z 80020508).

References

- Agapiou, A., Hadjimitsis, D.G., 2011. Vegetation indices and field spectroradiometric measurements for validation of buried architectural remains: verification under area surveyed with geophysical campaigns. *Journal of Applied Remote Sensing* 5. doi:10.1117/1.3645590.
- Augusto, L., Bakker, M.R., Meredieu, C., 2008. Wood ash applications to temperate forests ecosystems – potential benefits and drawbacks. *Plant and Soil* 306, 181–198.
- Bewley, B., Raczkowski, W., 2002. *Aerial Archaeology. Developing Future Practice*. IOS Press, Washington DC.
- Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108, 583–595.
- Černý, J., Balík, J., Kulhánek, M., Časová, K., Nedvěd, V., 2010. Mineral and organic fertilization efficiency in long-term stationary experiments. *Plant Soil and Environment* 56, 28–36.
- Challis, K., Kinsey, M., Howard, A.J., 2009. Airborne remote sensing of valley floor geo-archaeology using Daedalus ATM and CASI. *Archaeological Prospection* 16, 17–33.
- Cowley, D.C., Standing, R.A., Abicht, M.J., 2010. *Landscapes Through the Lens. Aerial Photographs and the Historic Environment*. Oxbow Books, Oxford.
- Cowley, D.C., 2002. A case study in the analysis of patterns of aerial reconnaissance in a lowland area of Southwest Scotland. *Archaeological Prospection* 9, 255–265.
- Crawford, O.G.S., 1924. *Air Survey and Archaeology*. In: *Ordnance Survey Professional Papers New Series* 7.
- Dambrine, E., Dupouey, J.L., Laut, L., Humbert, L., Thion, M., Beaufils, T., Richard, H., 2007. Present forest biodiversity patterns in France related to former Roman agriculture. *Ecology* 88, 1430–1439.
- Doneus, M., 2001. Precision mapping and interpretation of oblique aerial photographs. *Archaeological Prospection* 8, 13–27.
- Dupouey, J., Dambrine, E., Laffite, J.D., Moares, C., 2002. Irreversible impact of past land use on forest soils and biodiversity. *Ecology* 83, 2978–2984.
- Erneé, M., Majer, A., 2009. Burial rites: uniform or diverse? Interpretation of the results of phosphate soil analysis at the Únětice culture burial site in Prague 9 – Miskovice. *Archeologické Rozhledy* 61, 493–508.
- Evans, R., Jones, R.J.A., 1977. Crop marks and soils at two archaeological sites in Britain. *Journal of Archaeological Science* 4, 63–76.
- Fassbinder, J.W.E., 2010. Geophysical prospection of the frontiers of the Roman Empire in Southern Germany, UNESCO world heritage site. *Archaeological Prospection* 17, 129–139.
- Gallo, D., Ciminale, M., Becker, H., Masini, N., 2009. Remote sensing techniques for constructing a vast Neolithic settlement in Southern Italy. *Journal of Archaeological Science* 36, 43–50.
- Gojda, M., Trefný, M., 2011. *Archaeology in the Landscape Around the Říp Mountain*. University of West Bohemia, Plzeň.
- Gojda, M. (Ed.), 2004. *Ancient Landscape, Settlement Dynamics and Non-Destructive Archaeology*. Academia, Prague.

- Gojda, M., 2005. Features, sites and settlement areas in the view of air survey (Bohemia, 1992–2003). In: Burgeois, J., Meganck, M. (Eds.), *Air Photography and Archaeology 2003. A Century of Information*, Gent, pp. 101–111.
- Gojda, M., 2006. The archaeology of lowlands: a few remarks on the methodology of aerial survey. In: Meier, T. (Ed.), *Landscape Ideologies. Series Minor 22. Archaeolingua*, Budapest, pp. 117–123.
- Haberle, J., Svoboda, P., Krejčová, J., 2006. Uptake of mineral nitrogen from subsoil by winter wheat. *Plant Soil and Environment* 52, 377–384.
- Hanson, W.S., Oltean, I.A., 2003. The identification of Roman buildings from the air: recent discoveries in Western Transylvania. *Archaeological Prospection* 10, 101–117.
- Hásek, V., Kovárník, J., 1999. Aerial and geophysical prospection in archaeological research of prehistoric circular ditches in Moravia. *Archaeological Prospection* 6, 187–209.
- Hejzman, M., Kunzová, E., 2010. Sustainability of winter wheat production on sandy-loamy Cambisol in the Czech Republic: results from a long-term fertilizer and crop rotation experiment. *Field Crops Research* 115, 191–199.
- Hejzman, M., Smrž, Z., 2010. Cropmarks in stands of cereals, legumes and winter rape indicate sub-soil archaeological features in the agricultural landscape of Central Europe. *Agricultural Ecosystems and Environment* 138, 348–354.
- Hejzman, M., Ondráček, J., Smrž, Z., 2011. Ancient waste pits with wood ash irreversibly increase crop production in Central Europe. *Plant and Soil* 339, 341–350.
- Hlavinka, P., Trnka, M., Semerádová, D., Dubrovský, M., Žalud, Z., Možný, M., 2009. Effect of drought on yield variability of key crops in Czech Republic. *Agricultural and Forest Meteorology* 149, 431–442.
- Holliday, V.T., Gartner, W.G., 2007. Methods of soil P analysis in archaeology. *Journal of Archaeological Science* 34, 301–333.
- Kershaw, A., 2003. Hadrian's Wall national mapping programme – a world heritage site from the air. *Archaeological Prospection* 10, 159–161.
- Kirkegaard, J.A., Lilley, J.M., 2007. Root penetration rate – a benchmark to identify soil and plant limitations to rooting depth in wheat. *Australian Journal of Experimental Agriculture* 47, 590–602.
- Kirkegaard, J.A., Lilley, J.M., Howe, G.N., Graham, J.N., 2007. Impact of subsoil water use on wheat yield. *Australian Journal of Experimental Agriculture* 58, 303–315.
- Krček, M., Slamka, P., Olšovská, K., Brestič, M., Benčíková, M., 2008. Reduction of drought stress effect in spring barley (*Hordeum vulgare* L.) by nitrogen fertilization. *Plant Soil and Environment* 54, 7–13.
- Křivánek, R., 2006. Magnetometric prospection of various types of large ditched enclosures in Bohemia. *Archaeological Prospection* 13, 25–43.
- Kuna, M. (Ed.), 2007. *Archeologie Prvěkých Čech – Pravěký Svět a Jeho Poznání*. Academia, Prague.
- Kunzová, E., Hejzman, M., 2009. Yield development of winter wheat over 50 years of FYM, N, P and K fertilizer application on black earth soil in the Czech Republic. *Field Crops Research* 111, 226–234.
- Kunzová, E., Hejzman, M., 2010. Yield development of winter wheat over 50 years of nitrogen, phosphorus and potassium application on greyic Phaeozem in the Czech Republic. *European Journal of Agronomy* 33, 166–174.
- Lasaponara, R., Masini, N., 2007. Detection of archaeological crop marks by using satellite QuickBird multispectral imagery. *Journal of Archaeological Science* 34, 214–221.
- Majer, A., 1996. Cropmarks from the vegetation colour process perspective. *Archeologické Rozhledy* 48, 264–272.
- Mitchell, H.H., Hamilton, T.S., Steggerda, F.R., Bean, H.W., 1945. The chemical composition of the adult human body and its bearing on the biochemistry of growth. *The Journal of Biological Chemistry* 158, 625–637.
- Nedvěd, V., Balík, J., Černý, J., Kulhánek, M., Balíková, M., 2008. The changes of soil nitrogen and carbon contents in a long-term field experiment under different systems of nitrogen fertilization. *Plant Soil and Environment* 54, 463–470.
- Nielsen-Marsh, C.M., Hedges, R.E.M., 2000. Patterns of diagenesis in bone I: the effects of site environments. *Journal of Archaeological Science* 27, 1139–1150.
- Pavlík, M., Pavlíková, D., Balík, J., Neuberger, M., 2010. The contents of amino acids and sterols in maize plants growing under different nitrogen conditions. *Plant Soil Environment* 56, 125–132.
- Semelová, V., Hejzman, M., Pavlů, V., Vacek, S., Podrázský, V., 2008. The Grass Garden in the Giant Mts. (Czech Republic): residual effect of long-term fertilization after 62 years. *Agriculture Ecosystems and Environment* 123, 337–342.
- Šíp, V., Růžek, P., Chrpová, J., Vavera, R., Kusá, H., 2009. The effect of tillage practice, input level and environment on the grain yield of winter wheat in the Czech Republic. *Field Crops Research* 113, 131–137.
- Sorensen, M.L.S., Rebay-Salisbury, K., 2008. Landscapes of the body: burials of the Middle Bronze Age in Hungary. *European Journal of Archaeology* 11, 49–74.
- Šrek, P., Hejzman, M., Kunzová, E., 2010. 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. *Field Crops Research* 118, 183–193.
- Stanjek, H., Fassbinder, J.W.E., 1995. Soil aspects affecting archaeological details in aerial photographs. *Archaeological Prospection* 2, 91–101.
- Trier, Ø.D., Larsen, S.Ø., Solberg, R., 2009. Automatic detection of circular structures in high-resolution satellite images of agricultural land. *Archaeological Prospection* 16, 1–15.
- Trnka, M., Dubrovský, M., Svoboda, M., Semerádová, D., Hayes, M., Žalud, Z., Wilhite, D., 2008. Developing a regional drought climatology for the Czech Republic. *International Journal of Climatology* 29, 863–883.
- Verhoeven, G.J., Schmitt, K.D., 2010. An attempt to push back frontiers – digital near-ultraviolet aerial archaeology. *Journal of Archaeological Science* 37, 833–845.
- White, R.G., Kirkegaard, J.A., 2010. The distribution and abundance of wheat roots in a dense, structured subsoil – implications for water uptake. *Plant Cell and Environment* 33, 133–148.