

Pedogenesis of Chernozems in Central Europe — A review

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Received 23 August 2005; received in revised form 30 August 2006; accepted 24 January 2007

Available online 3 April 2007

Abstract

Since Dokuchaev's investigations of Russian Chernozems, Central European Chernozems were established as steppe soils, with their pedogenesis dominated by humus accumulation as a result of dry continental climate and steppe vegetation, with carbonaceous parent material and bioturbation as other prerequisites. The WRB-FAO classification defined Chernozems by their morphological characteristics, but was biased by the climo-genetic formation model. However, the assumption that modern Central European Chernozems are relics of steppe soils conflicts with palaeobotanical evidence from an early reforestation that started in the Late Glacial, and also with pedological studies that dated Chernozem formation to the Early Holocene.

In this review we compile the most important literature on pedogenesis of Central European Chernozems since the 1920s, according to the soil forming factors climate, time, vegetation, relief and man.

Our review demonstrates that there is no consensus on the factors controlling the formation, conservation and degradation of Central European Chernozems in published literature. We found that (1) no absolute time of formation could be stated so far, and that (2) Central European Chernozems formed not only under steppe but also under forest vegetation; (3) the spatial distribution of Chernozems and Phaeozems did not correlate with climate conditions or topographic position, and (4) until now no other factors were considered to be responsible for Chernozem development. Recent studies showed that these unknown factors could include anthropogenic activity and vegetation burning as they could form black soils or strongly affect the composition of soil organic matter.

We concluded that not all soils classified as Chernozems in Central Europe are steppe soils and thus, as they do not necessarily reflect past climate, the classification may be misleading.

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Keywords: Chernozem; Phaeozem; Central Europe; Pedogenesis; Literature review

1. Introduction

Since Vassilij V. Dokuchaev's investigations in Russia, Chernozems were defined as steppe soils, with their pedogenesis dominated by the soil-forming factors of dry continental climate and steppe vegetation, with carbonaceous parent material, mainly loess, and bioturbation as other prerequisites (Dokuchaev, 1883, 1889). Dokuchaev's results for the Russian Chernozems were transmitted to Central European Chernozems

(e.g. by Hohenstein, 1919) and his definition was assumed to be universally valid for Eastern and Central Europe, although it was deduced from Russian soils.

But a comparison of the results of several studies concerning the formation of Central European Chernozems to Dokuchaev's definition of a Chernozem as a steppe soil showed that there are obvious discrepancies. By definition, Chernozems should be zonal soils, preserved under continental steppe conditions. However, continental climate occurred during the Late Glacial (c. 15000–11500 BP) but there is no evidence for the presence of Chernozems in Central Europe in the Late Glacial (Rohdenburg and Meyer, 1968; Iking, 1996). First evidence for fully developed Chernozems originate from the Early

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Holocene (c. 11500–5500 BP; Pre-Boreal to Atlantic) when warmer climate and forest vegetation dominated the Central European loess-belt.

The purpose of this review is to highlight the most important literature on Chernozems in Central Europe published since the 1920s. We did not discuss the Russian Chernozems, because this would exceed the limits of this paper. We also excluded black soils formed with a steady water supply, like Gleyic Chernozems and Gleyic or Stagnic Phaeozems. In this review, we want to discuss the following questions: (1) What is the definition of Chernozems, and (2) where do we find them? (3) When did Central European Chernozems form, and (4) is their formation bound to a certain climate and vegetation? (5) Which factors control conservation and degradation of Chernozems? (6) Are there unconsidered factors that influence Chernozem formation or their soil properties?

We focus on different soil forming factors potentially dominating the pedogenesis of Chernozems in Central Europe, i.e. time, vegetation, climate and, potentially overlooked so far, fire and man. We want to point out that there is no generally accepted consensus on the formation of Chernozems in Central Europe.

2. What is a Chernozem? Definitions and systematics

The World Reference Base for Soil Resources (FAO/ISRIC/ISSS, 1998) defined Chernozems as soils with mollic or chernic horizons of at least 20 cm and with a chrome of ≤ 2 for substrate finer than sandy loam or ≤ 3.5 for sandy loam or coarser substrate, respectively. Chernozems should contain concentrations of secondary carbonates starting with in 50 cm of the lower limit of the A horizon but at least within the top 200 cm, they should lack a petrocalcic horizon or secondary gypsum between a depth of 25 and 100 cm, and their diagnostic horizons are no other than argic, vertic or calcic. There should be no uncoated silt and sand grains on the structural ped surfaces. Usually, the dark mollic A horizon is situated on an argic or cambic B horizon. The mollic horizons are rich in organic matter (10–16%), are highly saturated with bases and react neutral. Typical features of Chernozems are the formation on mostly aeolian and carbonaceous sediments like loess, the occurrence in continental climate under tall-grass vegetation that provides high above-ground biomass of about 1.0–1.5 t ha⁻¹, and an intense bioturbation shown by krotovinas (animal burrows) (FAO/ISRIC/ISSS, 1998; Driessen et al., 2001).

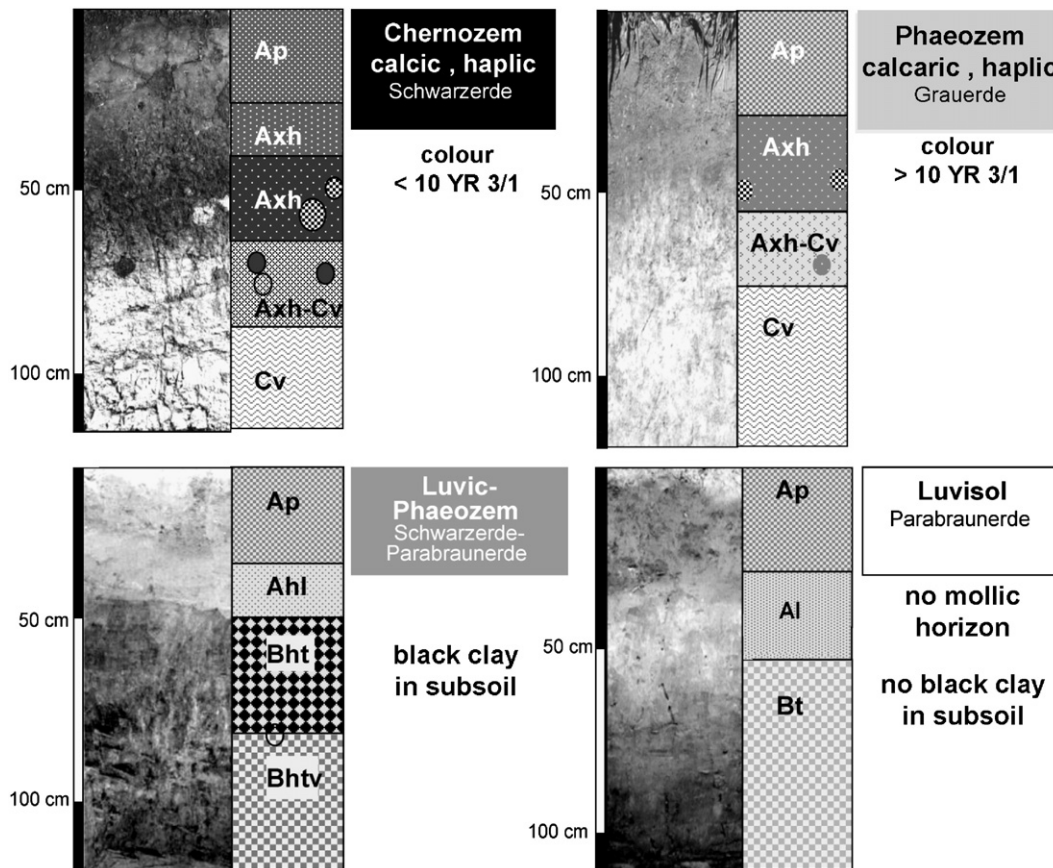


Fig. 1. Central European Chernozems and related soils as described in the German pedological literature. The Chernozem (‘Tschernosem’) has a dark mollic horizon and could have stagnic or gleyic properties. The latter do not appear in areas with lower water net balance, here secondary carbonates become more frequent. Increasing precipitation and leaching leads to the development of first Haplic, then Cambic and Luvic Chernozems and finally Luvic Phaeozems (‘Tschernosem-Parabraunerde’). Some soils have properties that fit to the Chernozem definition, with the exception that their mollic horizon is greyish and not dark brownish to black (‘Grauerden’; term is not recognised in the official German classification). These grey soils can contain secondary carbonates (calcic) or can have gleyic or stagnic properties and were assigned to the Phaeozems. Luvisols (‘Parabraunerde’) develop after stronger leaching and translocation of clay.

Chernozems can develop in to Phaeozems, and the characteristics of Phaeozems resemble those of Chernozems. They have a mollic horizon and a base saturation of at least 50%. They should not contain secondary carbonates up to 100 cm depth and have no diagnostic horizons other than albic, argic, cambic or vertic. Compared to Chernozems, Luvic Phaeozems occur in more humid regions, have higher rates of leaching and therefore lack carbonates. Argic B horizons seem to be relics from stronger leaching and indicate the development towards Luvisols (FAO/ISRIC/ISSS, 1998; Driessen et al., 2001). However, the soil map of the world mentions the subunit Calcaric Phaeozem with more than 2% CaCO₃ (FAO-UNESCO, 1981).

The definitions of Chernozems and Phaeozems by FAO-WRB stress their morphology but were biased by the climo-genetical background. This makes it difficult to assign all Central European Chernozem subunits (e.g. for Germany described by Ad-hoc-AG Boden, 2005; see also Altermann et al., 2005) to the FAO-WRB classification. The differences between the soil units described in the German pedological literature are explained in Fig. 1.

Stagnic and Gleyic Phaeozems developed under different conditions than soils in steppe areas (Scheffer and Meyer, 1965). However, the German definition of a ‘Schwarzerde’ (black earth) subsumes soils with greyish to black (Chroma < 3.5, Value ≤ 4) Axh horizons ≥ 40 cm and either with secondary

carbonates (‘Kalktschernosem’) or without (‘Tschernosem’). The term ‘Tschernosem’ includes not only Chernozem or Phaeozem subunits but also Kastanozems, Gleysols and Fluvisols and implies bioturbation as specific formation qualification (Ad-hoc-AG Boden, 2005). Despite these definitions, the terms ‘Schwarzerde’ and ‘Tschernosem’ were usually related to the appearance of steppe soil relics in Central Europe, and therefore Chernozems or Phaeozems (Kossowitsch, 1912; Hohenstein, 1919; Wilhelmy, 1950; Altermann and Mania, 1968). Their dark colour was assumed to originate from humic acids coating clay minerals that form stable dark complexes (e.g. Laatsch, 1938; Rochus, 1979; Mückenhausen, 1985a). Kahle et al. (2002) found that Chernozem organic matter accumulates in the clay fractions and seems to be associated with the mineral phase.

3. Where do we find Chernozems and Phaeozems in Europe?

The distribution of Chernozems and Phaeozems in Central Europe is shown in Fig. 2. The Eurasian Chernozem occurs in an area stretching from the Southern Urals to the Ukraine, passing through Moldavia and narrowing in the Danube basin (FAO-UNESCO, 1981; Bronger, 2003). Chernozems were characterized in Romania (Schönhals et al., 1982), Bulgaria (Koinov, 1968), in the Alföld and Banat regions in Hungary

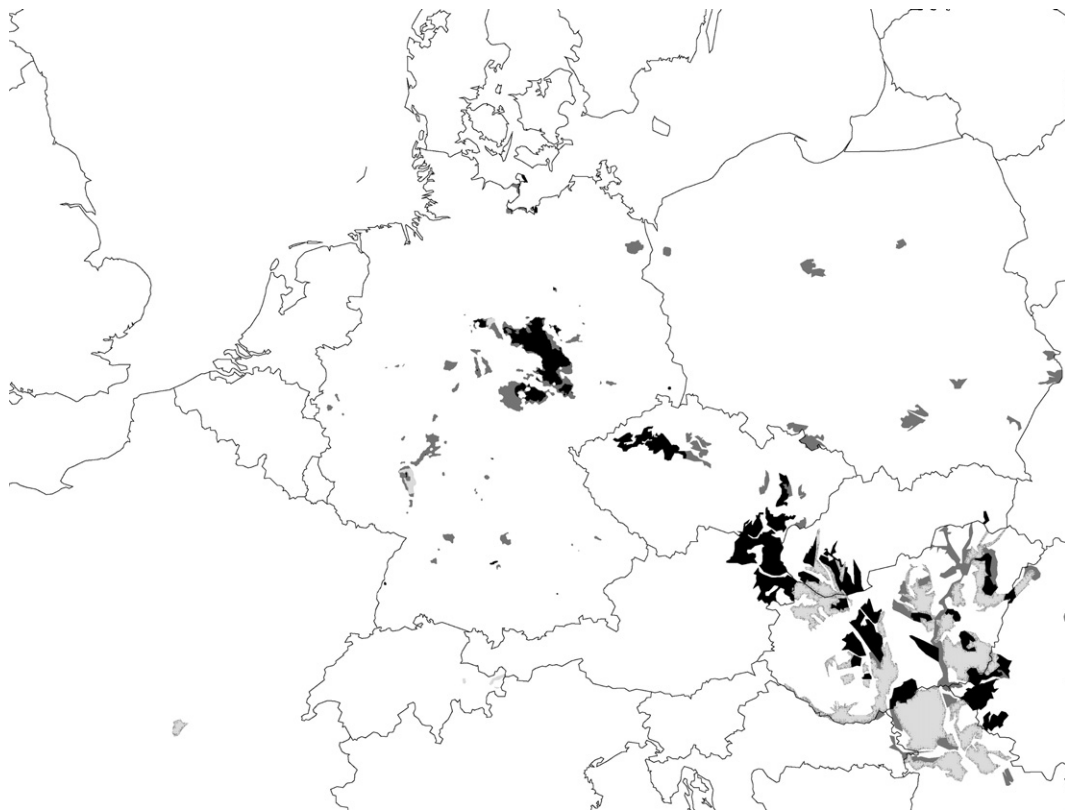


Fig. 2. Distribution of Chernozems and Phaeozems in Central Europe. The map shows the following varieties of Chernozems and Phaeozems: Chernic, Calcaric and Vermic-calcaric Chernozems (black); Luvic Chernozems, Stagnic, Luvic and Haplic Phaeozems (dark grey); Calcaric, Gleyic and Calcaric-fluvic Phaeozems (light grey). Data source: Soil Geographical Data Base of Eurasia at Scale 1:1 000 000 (SGDBE) version 2, http://eusoils.jrc.it/wms/Metadatas/Somis_metadatas.htm; Bundesanstalt für Geowissenschaften und Rohstoffe, 1995; supplemented by E. Gehrt based on own surveys and information from the different institutes of the German state geological survey.

Table 1
Review of factors determining formation and preservation of Central European Chernozems and Phaeozems

Authors	Soil name		Location	Climate		Vegetation			Time		Man	Fire
	As given by authors	FAO-WRB		Precipitation/ evaporation, temperature	Soil water	Uncertain	Steppe	Forest– teppe	Forest	Late Glacial		
Hohenstein (1919)	Schwarzerde (Tschernosem)	Chernozem	Poland	x			x					
(Stremme, 1926, 1936)	Tschernosem	Chernozem	Central Germany	x	x		x			x		
Meyer (1926)	Schwarzerde	Chernozem	Central Europe	x			x					
Schlüter (1929)	Schwarzerde	Chernozem	Central Germany							x	x	
(Laatsch, 1934, 1938, 1957)	Schwarzerde	Chernozem	Central Germany	x			x			x		
Schwarz (1948)	Schwarzerde	Chernozem	Central Germany	x			x			x		
Wilhelmy (1950)	Schwarzerde	Chernozem	Central/Eastern Europe	x			x			x		
Fink (1956)	Tschernosem	Chernozem	Austria	x			x			x		
Harth (1956)	Schwarzerde	Phaeozem	Upper Rhine Valley	x			x			x	x	
Scheffer and Meyer (1958)	Feuchtschwarz–Gleyic erde	Chernozem	Lower Saxony		x			x				
(Zakosek, 1962, 1991)	Rheintal–Tschernosem	Phaeozem	Upper Rhine Valley	x			x			x	x	x
Hohnvehlmann (1963)	Parabraunerde (Schwarzerde)	Phaeozem	Westphalia	x	x		x			x		
Scheffer and Meyer (1963)	Schwarzerde	Chernozem/Phaeozem	Lower Saxony	x	x		x	x		x		
Baumann et al. (1964)	Siedlungsschicht	Anthrosol	Saxony								x	
Czerny (1965)	Schwarzerde	Chernozem	Central Germany	x			x			x		
Kopp (1965)	Schwarzerde	Chernozem	Lower Rhine Basin	x			x			x		
Scheffer and Meyer (1965)	Feuchtschwarzerde	Gleyic Chernozem	Lower Saxony		x		--	--	--	x		
Wichtmann (1965)	Schwarzerde	Phaeozem	Westphalia							x		
Meyer (1966)	Feuchtschwarzerde	Gleyic Chernozem	Lower Saxony		x					x		
Altermann and Mania (1968)	Tschernosem	Chernozem	Central Germany	x			x			x	x	
Rau (1968)	Tschernosem	Chernozem	Central Germany	x			x			x		
Roeschmann (1968)	Tschernosem	Phaeozem	Lower Saxony	x	x		x	x		(x)	x	
Rohdenburg and Meyer (1968)	Schwarzerde	Chernozem/Phaeozem	Germany	x	x			x		x		
Scharpenseel and Pietig (1969)	Fossile Schwarzerde n	Phaeozem	Germany							x		
Altmannsberger (1971)	Tsche mosem	Chernozem/Phaeozem	Hesse	x				x				
Bailly (1972)	Schwarzerde	(Gleyic) Chernozem	Lower Saxony	x	x	x	x					
Leser and Maqsud (1975)	Steppenboden	Chernozem	Upper Rhine Valley	x			x			x		x
Schalich (1981)	Schwarzerde	Phaeozem	Lower Rhine Basin	x			x			x		
Bork (1983)	(Feucht) Schwarzerde	(Gleyic) Chernozem	Lower Saxony		x			x		x		
Müller (1982)	Schwarzerde	Chernozem	Central Germany, Upper Rhine Valley	x	x		x	x		x	x	
	Schwarzerde	Phaeozem	Westphalia, Lower Rhine	x				x		x		

(continued on next page)

Table 1 (continued)

Authors	Soil name		Location	Climate	Vegetation				Time		Man	Fire
	As given by authors	FAO-WRB			Precipitation/evaporation, temperature	Soil water	Uncertain	Steppe	Forest–teppe	Forest		
			Basin									
Roeschmann et al. (1982)	Schwarzerde	Chernozem/Phaeozem	Lower Saxony	x	x			x		x		
Sabel (1982)	Tschernosem	Chernozem/Phaeozem	Hesse	x	x	--	--	--				
Schönhals et al. (1982)	Brauner Rheintal–Tschernosem	Phaeozem	Upper Rhine Valley	x				x				
	Donau–Tschernosem	Chernozem/Phaeozem	Romania	x				x				
Mückenhausen (1985b)	Tschernosem	Chernozem/Phaeozem	Germany	x				x		x		
Thiemeyer (1989)	Tschernosem–Parabraunerde	Phaeozem	Hesse	x	x			x		x		
Thater and Stahr (1991)	Parabraunerde–Tschernosem	Phaeozem	Suebia	x	x			x		x		
Gehrt et al. (1995)	Grauerde	Phaeozem	Lower Saxony					x		x		
Ehwald et al. (1999)	Schwarzerde	Chernozem	Central Germany	x	x			x		x		
Fischer-Zujkov et al. (1999)	Parabraunerde–Tschernosem	Phaeozem	Uckermark	x	x					x		
(Schmidt et al., 1999, 2002)	Chernozemic soil		Germany	--	--	--	--	--	--	--		x
(Schmid et al., 2001, 2002)	Archaeological soil		Bavaria								x	x
Scheffer/Schachtschabel (2002)	Tschernosem (Schwarzerde)	Chernozem/Phaeozem	Germany	x				x		x		

Authors (selection) in chronological order. X = yes, -- = no, () = uncertain.

(Szűcs, 1963), in the Vojvodina (Neigebauer et al., 1983), in Bohemia and Moravia (Hrasko et al., 1973), in the Pannonian Basin of Eastern Austria (Franz, 1955; Fink, 1956; Blum and Solar, 1986), in the East of Poznan in Poland (Hohenstein, 1919) and in the Central German Dry Area (e.g. Czerny, 1965; Altermann and Mania, 1968).

Phaeozems can be found in different varieties and do not appear in a defined area (FAO-UNESCO, 1981). We could not record all areas covered by the patchy distributed Phaeozems, or their spatial extent had to be exaggerated to show their appearance in Fig. 2. In Germany they occur in loess-covered regions, including Lower Saxony (Scheffer and Meyer, 1963; Bailly, 1972; Roeschmann et al., 1982), Rheingau and Rheinhessen (Hohenstein, 1920; Harth, 1956; Zakosek, 1962; Leser and Maqsud, 1975; Zakosek, 1991), near Stuttgart and Heilbronn (Müller, 1951), Westphalia (Hohnvehlmann, 1963; Wichtmann, 1965), Lower Rhine Basin (Kopp, 1965; Schalich, 1981), Lower Hesse (Haupenthal, 1978), Uckermark (Fischer-Zujkov et al., 1999) and the Wetterau Basin (Altmannberger, 1971). Phaeozems can be found in the Limagne basin in France (FAO-UNESCO, 1981; ISSS, 1996) and in alpine dry-valleys (Meyer, 1926; Frei, 1980; Blum and Solar, 1986; ISSS, 1996). In warm and dry Swiss alpine valleys, Phaeozems with mollic epipedons occur in altitudes between 600 and 1700 m a.s.l. They usually formed on a mixture of well drained calcareous and silicate parent material, like moraines (Frei, 1980). Soils on

the island of Poel (Baltic Sea) were classified as soils with phaeozem-like properties. They have dark mollic A horizons developed on sandy, not on silty loess-like parent material (Albrecht and Kühn, 2003). Similar soils can be found on the island of Fehmarn (Schimming and Blume, 1993) (Table 1).

4. Time — When did Central European Chernozems form?

Late Glacial and Early Holocene were discussed as possible times of Central European Chernozem pedogenesis (Kopp, 1965; Ehwald et al., 1999). Stratigraphical methods and radiocarbon dating were used to determine the age of a soil. But methodological problems, and because the ages vary over time, absolute ages are still not known.

4.1. Stratigraphical and palaeoecological evidence?

The possibility of a formation of Chernozems in the Late Glacial was supported by the occurrence of steppe conditions that were regarded as requirement for their development (Wilhelmy, 1950; Kopp, 1965). Proceeding from west to east, the warmer and more humid climate in the Early Holocene stopped the accumulation of humus material (Kopp, 1965). This view was encouraged by observations of relics of fully developed Chernozem found at archaeological sites related to

the Early Neolithic Period (5500–5000 BC). Thus, Chernozem formation should have been completed before 5500 BC (Schalich, 1981). It was assumed that the first Neolithic settlers (Linienbandkeramik, 5500–5000 BC) found the Central European loess areas covered with Chernozems that provided a basis for the institution of agriculture (Bogucki, 1988; Lüning, 2000).

Black humic horizons under a layer of Laacher See Tephra, the volcanic outburst was dated 12,900 cal. BP, were described by Roeschmann (1968) as remnants of Chernozems formed in the Late Glacial, whereas Rohdenburg and Meyer (1968) denied the existence of fully-developed Late Glacial Chernozems in favour of Calcaric Regosols with less profound humic horizons. Rohdenburg (1978) suggested that a later pedogenesis in the Early Holocene could have affected the substrate under the thin layer of Laacher See Tephra, leading to a misinterpretation of the humic horizons found under the ash layer. Also Altermann and Mania (1968) examined soils buried under Laacher See Tephra and concluded that the formation of Chernozems started in the Younger Dryas. The authors identified the examined horizon as part of an early Chernozem because of high grey humic acid concentrations. Reconsidering the profile descriptions, it could be stated that the fossil A horizon in the profile Weinberg near Schadeleben was only 12 cm thick, did not show any homogeneous humus distribution and had a relatively low carbon content of 3.4 g kg^{-1} . In contrast, the Chernozem described at Salziger See developed in Atlantic. However, the A horizon is still less than 40 cm thick and it is situated on material with gleyic properties. Still, there are no hints for profound humic horizons under Laacher See Tephra and therefore in Late Glacial (Iking, 1996).

Most authors and textbook knowledge preferred the Early Holocene as time of Chernozem formation (Czerny, 1965; Rau, 1968; Roeschmann et al., 1982; Scheffer/Schachtschabel, 2002), based on the research of Laatsch (1934). He assumed that Chernozems formed in Boreal to Sub-Boreal, mainly in Atlantic (c. 7800–5700 BP). His main argument was that merely more favourable climatic conditions than in Last Glacial would yield enough plant biomass to form the profound mollic horizons, i.e. a warm and moist spring to enhance plant growth alternating with dry hot summers and cold winters when decomposition processes were halted.

4.2. Radiocarbon dating

When using the radiocarbon method, reliable material for dating would be charcoal or wood particles separated from soils. Measuring extracted humic acids does not yield absolute ages, but the apparent mean residence time of soil organic matter, which is a minimum estimate of soil ages. It is not possible to compare these ages to each other or relate them to certain time periods (Geyh, 1983; Scharpenseel and Becker-Heidmann, 1992).

Radiocarbon dating has, since the 1960s, been used to determine the ages of Central European Chernozems and Phaeozems. Scharpenseel and coworkers dated a large number of soil samples (Scharpenseel and Pietig, 1969; Scharpenseel et al., 1996) but until now, a precise date of Chernozem forma-

tion could not be confirmed. To determine ages for Chernozems, Scharpenseel and Pietig (1969) dated the soil organic matter (extracted humic acids) of a Chernozem A horizon covered by Laacher See Tephra, which therefore was regarded as being formed in the Late Glacial. A sample taken from material undisturbed by roots was dated $10,580 \pm 80$ BP (sample ‘Michelsberg II’). The authors concluded that the ‘Michelsberg II’ sample would give an absolute age and that Chernozems could have formed in the Late Glacial, presumably since Bølling (Scharpenseel and Pietig, 1969). On the other hand, Rohdenburg and Meyer (1968) disproved the existence of profound humic horizons in Late Glacial, and the age of the ‘Michelsberg II’ sample would be the age of a Calcic Regosol, which could represent an initial state of a Chernozem but not yet a fully developed one. Other measured maximum ages of Chernozems and Phaeozems, the oldest ages measured in the deepest part of the soil profiles published by Scharpenseel et al. (1968), covered some thousands of years, from 5550 ± 80 BP (4490–4260 BC) (sample ‘Söllingen D’) to 2560 ± 60 BP (810–540 BC) (sample ‘Wallertheim’). A black soil from Fehmarn (Baltic Sea) dates to the Middle Ages (1850 ± 70 BP or 560–770 AD) (sample Grossenbrode, Ostholsteen A).

Until recently, black soil remnants in Early Neolithic (5500–5000 BC) settlements were classified as remains of Chernozems. However, most data published by Scharpenseel et al. (1996) revealed younger ages of these remnants, most of them related to the period 4500–2200 BC (Younger to End Neolithic). This was supported by AMS ^{14}C ages of charred organic material (black carbon) deriving from different German Chernozems (Schmidt et al., 2002). Unlike single charcoal particles, black carbon data could give mean apparent ages of fire events. The different ages could indicate that Chernozems formed over a longer time period than thought before (Gehrt et al., 2002; Schmidt et al., 2002).

5. Vegetation — Formation under forests or after all still a steppe soil?

Dokuchaev (1883, 1889) concluded that Russian Chernozems formed under continental climate and steppe vegetation. Earlier, it was assumed that they developed under moist and wet conditions like Stagnic or Gleyic Chernozems (WRB-FAO; Bell and McDaniel, 2000). Dokuchaev stated that the soil forming factors interact and that climate would not be the dominating factor (Ehwald, 1984), and steppe vegetation was considered a main prerequisite for the formation of Chernozems (Laatsch, 1934; Driessen et al., 2001). Thus, the recent Chernozems and Phaeozems in Central Europe were regarded as relics of former steppe climate and vegetation (Wilhelmy, 1950).

Palynological evidence set the beginning of reforestation in Central Europe to the end of the Late Glacial (Firbas, 1949). The Central German dry region was covered with extensive forests since approx. 9500 BP (Preboreal) (Lange, 1965; Litt, 1992) and the Pannonian Basin was covered with open forests since Boreal (Havinga, 1972). Therefore, a formation of Central European Chernozems in the Early Holocene would not have occurred under steppe vegetation.

Scheffer and Meyer (1963) warned to draw conclusions from the existence of Chernozems to former climate and vegetation and suggested that they could have formed under forests. Scheffer et al. (1959/60) and Rohdenburg and Meyer (1968) gave evidence for a development of black soils under forests when low precipitation or stagic conditions stop decalcification. Ehwald et al. (1999) summarized the recent discussion about the formation of Chernozems in the Central German dry area. Here, pollen data suggested that the replacement of the steppe vegetation by birch and pine started in Preboreal and was completed in Atlantic with the appearance of deciduous forests. However, the investigation of fossil mollusc fauna lead Mania and Preuss (1975) to conclude that steppe vegetation was still present in Atlantic. But the mollusc fauna gives evidence only for the local vegetation history, whereas palynological data represents a larger region. Moreover, the molluscs originated from colluvial sediments, and a lack of vegetation to cover soil is a precondition for erosion and subsequent colluviation. The expansion of deciduous forests during Atlantic would be the more convincing scenario (Ehwald et al., 1999).

Ehwald et al. (1999) tried to elucidate the problem of Chernozems formed under forest by comparing Central German soils with Eastern European and Western Siberian soils. In Russia, Typical and Leached Chernozems occur under farmland and open deciduous forests. These soils should correspond to the German Chernozems under farmland. The Russian Grey Forest Soils, covered by dense forests, relate to the Central European Phaeozems and Luvisols. The examination of humic horizons of Chernozems in the steppe region near Kursk seemed to prove the unchanged conservation of Chernozems under open deciduous forests during some thousands of years. This could be an evidence for their genesis under an open forest or a forest–steppe (Ehwald et al., 1999). More examples for Chernozems under open forests were described in Austria (Franz, 1955).

A strong argument for a development of Chernozems under steppe vegetation was the existence of burrows (krotovinas) built by hamsters (*Cricetus*) or ground squirrels (*Citellus*), which live in open landscapes. Their soil-mixing activity was supposed to be essential for the formation of the mollic A horizon. In the Central German dry area only the existence of hamsters could be proved until now, but they probably inhabited the region after agriculture was established (Lange, 1965; Ehwald et al., 1999). More arguments against bioturbation as major soil forming process would be the existence of laminated Chernozems in Lower Saxony (Gehrt et al., 1999) and the results of radiocarbon dating, which showed an increase of age of soil organic matter with increasing soil depth (Scharpenseel et al., 1986).

6. Climate and relief — Conservation and degradation of Chernozems

Based on the assumption that Chernozems are steppe soils, a model was developed concerning conservation and degradation affected by climatic changes (e.g. Rau, 1968 for Central Germany). Chernozems formed under steppe conditions were expected to stay preserved in regions with a balanced or negative water balance. In Central Europe, this would be in geographical

regions with a mean annual precipitation of less than 500 mm, as stated by Meyer (1926). With increasing precipitation and leaching, the translocation of clay covered with humic material started and Chernozems were transformed into Phaeozems, Luvisols or Albeluvisols (Rau, 1968; Driessen et al., 2001). This degradation process was also described for Russian soils, where Alexandrovskiy and Chichagova (1998) investigated Luvisols with a fossil humus horizon and explained its formation with a climate change. After a Chernozem developed in Early and Middle Holocene, an increase in precipitation led to humus degradation in Late Holocene. During 2000 to 3500 years the Chernozem was transformed to a Luvisol, which still contains Chernozem material as a second A horizon.

The climo-genetic model was adopted to generate a chronology of Chernozem formation and degradation relating to climate change and archaeological phases. According to that chronology, the formation would have been completed before the Early Neolithic Period (5500–5000 BC), and leaching and degradation would have started with the onset of warmer and more humid Atlantic climate before the Bronze Age (before 2200 BC). Therefore, the Central European Chernozems should have stayed preserved in areas with negative water balance, whereas in other areas they transformed into Luvic Phaeozems or even Haplic Luvisols which do not show traces of their chernozemic past anymore (Scheffer and Meyer, 1963; Schlich, 1981).

Some authors referred to the factors relief and hydrological conditions: Chernozems were assumed to be better preserved under soil water supply that could stop the process of decalcification (Roeschmann, 1968; Thater and Stahr, 1991). On the other hand, black soils affected by high water levels (Gleyic or Stagnic Chernozems; FAO-WRB) could not only be preserved but may even have been formed under wet conditions (Scheffer and Meyer, 1958). Black Chernozem material could also be protected under colluvial sediments, especially when calcareous material stopped the leaching process (Sabel, 1982).

However, the factors affecting the spatial distribution of Chernozems are not well-known yet. Although most authors stressed a change of climate, this factor alone could not explain the present distribution of Chernozems. Stremme (1936) and Bailly (1972) could not correlate precipitation and the distribution of Chernozems, and Sabel (1982) stressed the importance of relief position for Chernozem preservation. Altermann and Fiedler (1975) found that the primary carbon content of the loess parent material is of greater importance to the pedogenesis of Chernozems than microclimate.

In fact, Chernozems often appear in patches but not in extensive covers, with no obvious relation to soil forming factors as climate or relief. Examples were given by Bailly (1972) and Gehrt et al. (1995, 2002) for Lower Saxony, where grey ('Grauerde') and black soils ('Schwarzerde') are distributed in sharply defined neighbouring patches without any differences in parent material, relief position or soil properties (description in Fig. 1). Bailly (1972) investigated Chernozems in Northern Germany and found no direct correlation between their distribution and climate, relief, parent material, hydrology or distribution of forest and farmland. He suggested that still unknown factors influenced the preservation of Chernozems. Kleber et al.

(2003) indicated that the patchy distribution of Chernozems could be explained by prehistoric anthropogenic influence on Chernozem pedogenesis.

7. Man and fire — The missing factors?

7.1. Charred organic matter as colouring agent

Up to now, the dark brown to black colour of Chernozem A horizons was attributed to humic acids that cover clay minerals or are bound between the layers of clay minerals. These resistant clay–humus-complexes remained in the argic subsoil horizons of leached and degraded Chernozems or Phaeozems (Greenland, 1971; Gebhardt, 1971; Rochus, 1979).

In contrast, some black soils seemed to inherit their dark colour from charred organic carbon or black carbon. The term black carbon describes a continuum of charred organic material, and black carbon could be used as a marker for vegetation fire. Up to 45% of the total organic carbon in Chernozems of Lower Saxony consisted of black carbon (Schmidt et al., 2002). In North American Chernozems, the proportion reached from 35% (Skjemstad et al., 2002; Glaser and Amelung, 2003) to 80% of soil organic carbon (Ponomarenko and Anderson, 2001). Russian Chernozems yielded 17% black carbon (BCA) up to a depth of 60 cm (Rodionov et al., 2006). Black carbon contributes to the highly aromatic and recalcitrant soil organic matter and could be recovered in the chemical fraction defined as humic acids (Haumaier and Zech, 1995; Skjemstad et al., 1996). Schmidt et al. (2002) calculated that one to seven fires would produce 1.7 g black carbon kg⁻¹ soil. Gehrt et al. (2002) assessed an annual input of 40 kg black carbon ha⁻¹ over 1000 years to reach the proportion of 20% black carbon in the soil organic matter of Chernozems of Lower Saxony.

However, black carbon represents a continuum of charred material, and the acquisition of black carbon data is still troublesome. A generally accepted definition of black carbon does not yet exist. Different analytical protocols are used to measure different fractions of black carbon. These protocols are based on the concept of chemical or thermal oxidation of labile organic matter and subsequent measurement of the relatively inert black carbon. The measurement of different fractions of black carbon with different methods obtains results that are not directly comparable (Bird, 1997; Schmidt et al., 2001).

Despite methodological problems, there is evidence for black soils having been formed as a result of black carbon incorporation in soils through vegetation burning in Australia (Skjemstad et al., 1996, 1997) and Africa (Kuhlbusch et al., 1996) or through the accumulation of hear thashes in Amazonian Brazil (Terra Preta; Glaser et al., 2001). Although the processes of incorporation and colouring are not yet clearly understood, soil colour (lightness) and amount of aromatic carbon, typical for black carbon, correlate (Spielvogel et al., 2004).

Black soil horizons in the Lower Rhine Basin (Northwest Germany) could be relics of anthropogenic fire management. The black soils occurred in patches, were always connected to anthropogenic pits and their soil properties differed very clearly from the surrounding Luvisols. The soil material contained

charcoal and black carbon (19–45% of soil organic carbon). The radiocarbon ages from charcoal and black carbon ranged from the Mesolithic period to the Middle Ages, with an emphasis in the Late Neolithic Period 4400–2200 BC) (Gerlach et al., in press). For the Late Neolithic Period, fire management could be supported by pollen records for Northern Europe (Iversen, 1941; Kalis and Meurers-Balke, 1998) and presumably also for the Lake Constance area (Rösch, 1993).

There is evidence that, next to black carbon or charcoal content, magnetic susceptibility of soil material may reflect past fires. Hanesch and Scholger (2005) measured the magnetic susceptibility in different Lower Austrian soils and found that Chernozems have the highest signals of all soil types ($77 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$). Bulgarian Chernozems gave similar values of $80 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ in the topsoil and $40 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ in the subsoil, respectively (Jordanova and Jordanova, 1999). The transformation of goethite or ferrihydrite to maghemite takes part during heating (Nørnberg et al., 2004) at temperatures as low as 220 °C (Sidhu, 1988). Zanelli et al. (in press) observed *in-situ* formation of maghemite up to 0.5 m deep in soils affected by forest fires in Southern Switzerland.

Circumstantial evidence suggests that vegetation fire could be a new formation factor in the genesis of black soils. Natural fires emerge rarely in Central European deciduous forests (Tinner et al., 1999). Therefore, vegetation fires ignited by humans may be a source for the black carbon found in Central European Chernozems.

7.2. The influence of human activity

Black soil remnants were often found in Neolithic settlement areas. Relics of black soils were preserved as fillings of pits, ditches or postholes and as remains of prehistoric surfaces. These black soils were described as relics of Chernozems, which should have been widespread in the loess-covered areas in Early Neolithic times. Scheffer and Meyer (1963) developed a model for Chernozem formation in Lower Saxony according to their observations on archaeological excavation sites. On some examined sites, e.g. in the Wetterau loess area (Hesse), the black soil horizon in the prehistoric settlement area corresponded to the surrounding Phaeozems (Thiemeyer, 1989). On other sites, as in the Lower Rhine Basin (Schalich, 1981), the black soils clearly differed from the surrounding Haplic Luvisols. In some cases, a mixture of Chernozems and anthropogenic organic material was described (Schwarz, 1948; Meyer, 1966; Grote, 1977).

Geochemical analysis of black soil material from prehistoric settlements and adjacent Phaeozems revealed that their chemical properties and pedogenesis were different. Pit fillings in a Neolithic settlement (Murr; Bavaria) contained high amounts of charred organic material (23–70% of total organic carbon), and the concentrations of charred material correlated with the soil colour. The dark material in the settlement area was a mixture of deposited waste material and soil (Schmid et al., 2001, 2002).

Baumann et al. (1964) analysed black pit fillings and the black surface layer in a Neolithic settlement. The pit fillings consisted of organic material, mainly waste or litter, which was

incorporated into the natural A horizon and was responsible for the dark colour. Furthermore, these black soils were located only in the settlement areas and gave no evidence for a former occurrence of Chernozems.

An evidence for anthropogenic influence on Chernozem formation could be the distribution of ‘Grauerden’ and ‘Schwarzerden’ in Lower Saxony. Black and grey soils formed a patchwork with sharp boundaries between the two soil units that were independent of natural causes. Remarkably, Neolithic settlements were mostly situated at the edges of the black soil patches, confirming the idea of black soils as relics of agriculture (Gehrt et al., 2002).

Farming may have different effects on conservation and formation of Chernozems. On the one hand, ploughing could enhance the degradation of humus and therefore Chernozems (Laatsch, 1957). On the other hand, farming was thought to simulate steppe conditions that facilitate the persistence of Chernozems, without regarding the climatic factors (Stremme, 1926). Leser and Maqsud (1975) and Zakosek (1962) suggested that agriculture could even reverse the degradation process, as in Rheinhessen, where Late Glacial Chernozems were leached in the Early Holocene but re-formed after the erosion of the former humic horizon under farmland that seemed to simulate steppe vegetation.

8. Conclusions

This review on the pedogenesis of Central European Chernozems revealed that the processes and factors affecting Chernozem formation and conservation are diverse. Published results often conflict with the definition of Chernozems as steppe soils formed under continental climate.

We found that: (1) No absolute age and time of Chernozem pedogenesis could be stated. Stratigraphical records and radiocarbon data showed that the formation in the Late Glacial, when steppes actually occurred in Central Europe, seems to be unlikely. The radiocarbon data gave Holocene ages spread over about 3700 years, and they gave mean apparent ages of fire events (charred organic matter) or the mean residence times of soil organic matter, but no absolute ages. (2) Chernozems could have formed under forest or at least under forest–steppe. Not the type of vegetation seems to dominate the formation of mollic horizons but soil processes which influence either the presence of bicarbonates or lead to reduced decomposition and therefore accumulation of organic matter. (3) Climate and relief influence Chernozem preservation, but often these factors alone are not sufficient to explain Chernozem distribution and occurrence in certain geographical regions (e.g. Lower Saxony). (4) Man and fire may influence Chernozem properties through agriculture or fire management tools and could be the missing factors that explain the spatial distribution of Chernozems and Phaeozems. Vegetation fire could form black soils or Chernozems that contain high properties of charred organic matter. The black soil material in prehistoric settlements, often interpreted as a proof for Chernozem distribution in the Early Holocene, is usually soil mixed with organic material deriving from anthropogenic activity and does not reflect natural soils.

Concluding, the term Chernozem summarizes different types of black soils that have the same appearance but different formation histories. The FAO-WRB classification of Chernozems and Phaeozems has a pedogenetical background and connects them to steppe soils. From this review, it seems that soils with Chernozem or Phaeozem properties have often been interpreted as witnesses of past climate in Central Europe by their appearance, although dark or black soils could have diverse formation histories. Thus, they do not have to reflect past climate, and the classification may be misleading. This review of Chernozems pedogenesis showed that further investigations are needed to uncover the different formation histories of black soils.

Acknowledgements

We wish to thank Stefan Pätzold and Gerd Welp for their helpful comments on a previous version of the manuscript and gratefully acknowledge the valuable contributions of two anonymous reviewers.

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