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Synthesis

Soil cultures – the adaptive cycle of agrarian soil use in Central Europe: an interdisciplinary study using soil scientific and archaeological research

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ABSTRACT. Today's global challenges (e.g., food security) are not unprecedented in human history. Starting with the Neolithic transition, the agricultural sector and society underwent several cultural and technological changes and endured natural challenges. These challenges and changes are analyzed by using the adaptive cycle metaphor and the social-ecological system as tools to show the complexity of human–environment interactions and their development. The analysis relies on archaeological, pedological, and botanical research, and demonstrates the importance of interdisciplinary work. Agrarian soil use as a social-ecological system persisted in Central Europe for 7000 years and underwent an adaptive cycle from the Neolithic transition to industrialization. With agriculture's mechanization, a second adaptive cycle started. The resilience of agrarian soil use for thousands of years shows that agriculture, as a human–environmental interaction, is adaptive to change. Understanding past agricultural challenges and changes using archaeological and soil scientific data puts the present development into a new perspective. A cultural perspective on soils might trigger soil protection and sustainable land use in a technical as well as political domain. Applying social-ecological system and adaptive cycle concepts to this interdisciplinary reconstruction of agrarian soil use illustrates their usefulness for archaeology and soil science.

Key Words: *archaeobotany; archaeology; adaptive cycle; agriculture; historical overview; social-ecological system; soil science*

INTRODUCTION

Global climate change, degradation and erosion of soils, rising social inequality, and food insecurity comprise today's major human challenges (Tilman et al. 2002, Blum and Eswaran 2004, Luterbacher et al. 2004, Battisti and Naylor 2009, Lal 2010, Foley et al. 2011). Studies of past human–environment interactions show that these are not unprecedented in history (Costanza et al. 2007, Caseldine and Turney 2010, Büntgen et al. 2011). Agriculture, as a system based on human–environmental interaction, also has had an impact on societies and the environment in Central Europe since its origin and spread from the Near East around 9500 BCE (Evans 2012).

The development of the agricultural system is analyzed using the concepts of the adaptive cycle and the social-ecological system (Gunderson and Holling 2002). The adaptive cycle is repeatedly used in research; for example, in the bioenergy sector in Northern Germany (Grundmann et al. 2012) or in the resilience of two contrasting social-ecological systems (Carpenter et al. 2001). Dorren and Imeson (2005) used it to develop a framework on soil erosion for Southern Limburg. Beier et al. (2009) investigated forest management in Alaska, and Allison and Hobbs (2004) expanded the use of the adaptive cycle to economics in their analysis of the Western Australian Agricultural Region. Zimmermann (2012) used a specification of the adaptive cycle to improve the understanding of mobility structures in prehistoric Europe. These examples show dynamic social-ecological systems, and demonstrate that the adaptive cycle is a useful tool for investigating the development of such systems.

In the following, agrarian soil use as a social-ecological system is introduced and analyzed using the adaptive cycle metaphor. Due to limited written sources for (pre)historic times, the analysis focuses on archaeological, pedological, palynological, and historical records that have been published by scientists of the respective disciplines. The aim is to investigate changes in agrarian soil use that are observable for the variables soil, crop, and technology. Is the adaptive cycle useful for explaining changes over several thousand years? What major changes led to a restructuring of the social-ecological system? Are the developments in the Neolithic comparable to industrialization? If so, are there implications for soil use in the future?

AGRARIAN SOIL USE AS A SOCIAL-ECOLOGICAL SYSTEM

A social-ecological system (SES) is characterized by the integration of natural and social components (Berkes and Folke 1998, Berkes et al. 2003, Berkes 2004). Social-ecological systems shape the world, and to understand them, it is necessary to split the bigger systems into smaller parts. However, the smaller systems remain part of other SESs. Our analysis focuses on agrarian soil use as an SES, which is part of a bigger SES, and in turn can be divided into smaller SESs on any temporal or spatial scale. The adaptive cycle metaphor (Gunderson and Holling 2002) is used as a theoretical framework for the narrative of agricultural history in Central Europe.

The main variable of the SES agrarian soil use is soil, which has been used agriculturally since the Neolithic transition. This use, or more precisely deforestation, has led to changes in the landscape and soil through erosion and accumulation processes. Under forests, the natural vegetation in Central Europe, erosion is minor because the roots of the vegetation stabilize the soil, preventing its erosion, and the canopy slows the rainfall (Pimentel and Kounang 1998, Geißler et al. 2012). Thus, the erosion and accumulation of soil material is connected to changes in vegetation cover. Prior to the Neolithic transition, this was related to climate events (Dreibrodt et al. 2010*a*). After the Neolithic

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Table 1. Several archaeobotanical studies that investigated the crops used in Central Europe in (pre-) historic times. The crops are named according to the study cited.

Author	Period	Region	Analysis	Crops identified in analysis
Bogaard et al. (2013)	Neolithic	Europe (examples in this table from Central Europe)	Whole grains from the same stratigraphic unit	Einkorn (*Triticum monococcum*), emmer (*T. dicoccum*), free-threshing wheat, naked barley (*Hordeum vulgare*), lentil (*Lens culinaris*), pea (*Pisum*)
Kirleis et al. (2012)	Neolithic	Northern Germany	Charred plant remains	(Naked) barley (*H. vulgare*), emmer (*T. dicoccum*), einkorn (*T. monococcum*), naked wheat (*T. aestivum*)
Bogaard et al. (2011)	Neolithic	Vaihingen, Enz, Germany	Chaff (glume base)	Einkorn (*T. monococcum*), emmer (*T. dicoccum*), “new type”, opium poppy (*Papaver somniferum*), feathergrass (*Stipa*)
Herbig (2009)	Neolithic	Lake Constance/ Upper Swabia, southwest Germany	Archaeobotanical (profile columns, surface samples)	Emmer (*T. dicoccon* Schrank), einkorn (*T. monococcum* L.), tetraploid naked wheat (*T. durum* Desf./*turgidum* L.), naked barley (*H. vulgare* ssp. *nudum*), opium poppy (*Papaver somniferum* L.), flax (*Linum usitatissimum* L.), single finds of pea (*Pisum sativum* L.), lentil (*Lens culinaris* L.)
Rösch (1987, 1993)	Neolithic to Bronze Age	Lake Constance, southwest Germany	Pollen analysis	Naked wheat (*T. aestivum/durum*), barley (*H. vulgare* L.), emmer (*T. dicoccum*), einkorn (*T. monococcum* L.), flax (*Linum usitatissimum* L.), opium poppy (*Papaver somniferum* L.), spelt (*T. spelta*), millet (*Panicum miliaceum*), pulses
Rösch (1996)	Late Neolithic to Bronze Age	Southwest Germany	Pollen analysis, charred plant macroremains	Einkorn (*T. monococcum*), emmer (*T. dicoccum*), naked wheat (*T. turgidum* s.l.), barley (*H. vulgare*), spelt (*T. spelta*), millet (*Panicum miliaceum*)
Kanstrup et al. (2014)	Neolithic to Iron Age	Denmark	Charred archaeobotanical cereal remains, isotope analysis	Emmer (*T. dicoccum*), spelt (*T. spelta*), naked barley (*H. vulgare*, var. Nudum)
Hubbard (1980)	Neolithic to Medieval period	Europe	Analysis of charred remains and pottery imprints	Barley (*H. vulgare*), emmer (*T. dicoccum* & *dicoccoides*), einkorn (*T. monococcum* & *bocoticum*), millet (*Panicum miliaceum*), oat (*Avena sativa* & *strigosa*), wheat (*T. aestivum* s.l.), rye (*Secale cereale*)
Mäckel et al. (2003)	Neolithic to Medieval period	Upper Rhine Lowlands, southern Black Forest, southwest Germany	Pollen analysis, evaluation of fossil soils	4000 BC: cerealia
Hjelle et al. (2012)	Neolithic to Medieval period	Norway	Pollen analysis, charred grains	Charred grains of *H. vulgare* (present from Late Neolithic to Early Bronze Age), cerealia pollen, mainly *Hordeum* type, but also *Avena* and *Triticum* type (Early Iron Age)
Behre (1992)	Neolithic to Medieval period	Central Europe	Carbonized grains, pollen diagram	Rye (*Secale cereale*) rare in Neolithic, increasing during pre-Roman Iron Age and Roman period and great increase in the Middle Ages
Wieckowska et al. (2012)	Neolithic to modern times	Großer Eutiner See, northern Germany	Pollen analysis	*Triticum*- and *Averna*-type pollen, *Secale* (Iron Age onward), *Hordeum* (Iron Age onward)
Dreßler et al. (2006)	Neolithic to modern times	Lake Dudinghausen, northern Germany	Pollen analysis	*Hordeum*, *Triticum*, *Secale* (Medieval period onward) --> cereal pollen increased in Modern times
Rösch (1998)	Neolithic to modern times	Southwest Germany	Review	*T. dicoccum*, *T. monococcum*, *H. vulgare*, *T. aestivum/durum*, *T. spelta* (minor in Neolithic but increase in Bronze Age), *Secale cereale* (minor in Neolithic but increase in Bronze Age), *Panicum miliaceum* (from Bronze Age on), *Setaria italica* (from Bronze Age on), *Avena* (from Bronze Age on), *Oryza sativa* (from Late Medieval period on), *Zea mays* (from modern times on), *Linum usitatissimum*, *Papaver somniferum*, *Brassica rapa*, *Camelina sativa*, *Cannabis sativa* (minor from Iron Age on), *Pisum sativum*, *Lens culinaris*, *Vicia ervilia* (few in Neolithic and in Iron Age), *V. faba* (from Bronze Age on), *V. sativa* (few in Roman and High Medieval times)
Rösch and Tserendorj (2011)	Bronze Age	Huzenbacher See, southwest Germany	Pollen analysis	Cerealia, secale (Medieval period)
Gauthier and Richard (2009)	Bronze Age	Lake Bourget, France	Pollen analysis	Cerealia
Stika and Heiss (2013)	Bronze Age	Europe	Review	Barley, emmer, einkorn, spelt, free-threshing wheat, millet, oat, rye
Dreslerova et al. (2013)	Bronze Age to Early Iron Age	Czech Republic	Charred plant macroremains	Emmer (*T. dicoccum* Schübl.), barley (*H. vulgare* L.), millet (*Panicum miliaceum* L.), spelt (*T. spelta* L.), later also naked wheat (*T. aestivum* L./*compactum* Host./*durum* Desf./*turgidum* L.), very low numbers of oat (*Avena sativa* L.) and rye (*Secale cereale* L.)

(con'd)

Kerig and Lechterbeck (2004)	Bronze Age to Medieval period	Lake Steisslingen, southwest Germany	Pollen analysis	*Triticum*, *Hordeum*, Cerealia, rye (Iron Age)
Rösch et al. (1992)	Roman to post-Medieval period	Southwest Germany, northern Switzerland	Review	Roman Period (1st–3rd century AD): *Panicum miliaceum*, *T. spelta*, *Secale cereale*, *H. vulgare*, *T. aestivum*, *T. monococcum*; in native Germania *T. monococcum*, *H. vulgare*, and *Secale cereale* Late Roman period (3rd–5th century AD): one site investigated on upper Danube with *H. vulgare*, *T. speta*, and *Avena* sp.; *T. aestivum*, *T. monococcum*, and *Secale cereale* (< 10%) Merovingian period (6th/7th century AD): *Avena* sp., *H. vulgare*, *T. spelta*, *T. aestivum*, *T. monococcum*, *Secale cereale* Carolingian-Ottonian period (8th–10th century AD): *T. aestivum*, *T. spelta*, *Avena* sp., *T. monococcum*, *H. vulgare*, and *Secale cereale* High Medieval period (11th–13th century AD): *Secale cereale*, *T. spelta*, *T. monococcum*, *Avena* sp., *H. vulgare*, *Panicum miliaceum*, *T. aestivum* Early modern period (16th–19th century AD): *Panicum miliaceum*, *Avena* sp., *H. vulgare*, *T. aestivum*, *Secale cereale*, *T. spelta*
Rebourg et al. (2003)	1493/1539	Southern Spain/ Germany	Literature review, genetic markers	Maize (*Zea mays* ssp. *mays*): several introductions
Hawkes and Francisco-Ortega (1993)	1567/1574	Gran Canaria/ Tenerife	Literature review	Potato (*Solanum tuberosum*/*Ipomoea batatas*)
Cassman (1999)	1967–1997	Global	Harvested area	Wheat (*T. aestivum* L.), rice (*Oryza sativa* L.), maize (*Z. mays* L.)

transition, land use change induced by humans led to erosion and the development of so-called colluvial deposits on foot slopes (Lang 2003, Leopold and Völkel 2007). The original reason for deforestation (e.g., clearance for fields or overgrazing) is difficult to determine; however, the analysis of colluvial deposits with ^{14}C dating and luminescence dating, and archaeobotanical and soil scientific research methods gives insight into the past (Eckmeier et al. 2007, Kadereit et al. 2010, Bogaard et al. 2013, Bakels 2014, Pietsch and Kühn 2014, Henkner et al. 2017). In international literature, the term "colluvial deposit" is unclearly connected to land use. Hereafter, the term "anthropogenic colluvial deposit" will be used when referring to soils, which studies suggest were formed due to land use change and agriculture.

Other variables of the SES agrarian soil use are climate and crops. Changes in crop plants are observable via archaeobotanical analyses (Rösch 1996). Crop refers to cereals (e.g., barley, wheat, rye), and excludes fruit, vegetables, and nuts. Climate change can be traced in ice cores, lake and ocean sediments, corals, tree rings, fossil leaves, and changes in pollen communities (Caseldine and Turney 2010, Aranbarri et al. 2014). The effect of climate on the settlement pattern of a region is discussed by experts (Berglund 2003, Zolitschka et al. 2003). While it is likely that climate change had an impact on agricultural practices, the extent is not clearly visible in the archives available for prehistoric times. Even with written sources, these refer to weather events and not climate per se. Therefore, climate effects on the SES agrarian soil use are not considered here.

The observable variable concerning society is the technological development of tools. The variable knowledge is difficult to define for times when no written sources exist. It is assumed here that technological development is accompanied by increasing knowledge. Knowledge/technology are used as one variable, which is traceable in archaeological finds. Thus, this study focuses only on observable variables that can be appropriately analyzed in the SES agrarian soil use, specifically soil, crops, and technology.

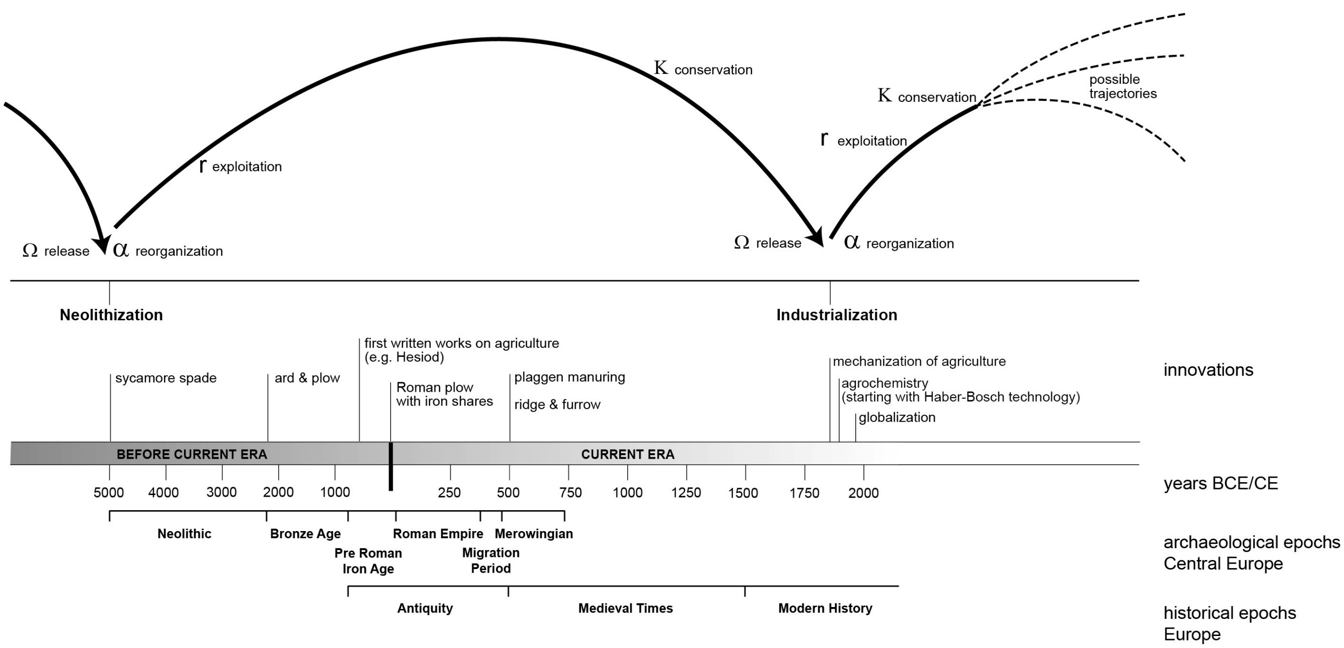
THE ADAPTIVE CYCLE OF THE SOCIAL-ECOLOGICAL SYSTEM AGRARIAN SOIL USE

The adaptive cycle was developed to explain ecosystem dynamics. It is composed of four phases: the r-phase of exploitation, the K-phase of conservation, the Ω-phase of release or creative destruction, and the α-phase of reorganization (Holling et al. 2002*a*, Holling and Gunderson 2002). This cycle is shaped by three properties: the potential of a system for change, the degree of connectedness between internal variables and processes, and the adaptive capacity of a system, its resilience as a measure of its vulnerability to unexpected shocks (Holling 2001). Holling and Gunderson (2002) state that the α-phase starts a process of reorganization during which potential and resilience are high but connectedness is low. During the r-phase, resilience remains high and connectedness is low. In the K-phase, connectedness increases while resilience decreases. The system becomes more vulnerable to disturbance. Due to this vulnerability, a disturbance can cause creative destruction in the Ω-phase in which potential is low. The sudden shift from the Ω- to α-phase leads to a new cycle with loose connections, high resilience, and an increasing potential. In this phase, different recombinations are possible, which makes the outcome of the reorganization unpredictable (Holling and Gunderson 2002).

The adaptive cycle shows that systems are dynamic. The SES agrarian soil use developed over time, and while some processes led, for example, to a deterioration of soil properties, overall development enabled the SES to grow and diversify. With the help of the adaptive cycle narrative, the emergence of our present-day agricultural system is analyzed. Changes of the variables or within the variables of the SES affect the adaptive cycle, shape the SES, and determine its resilience or vulnerability to unpredictable shocks (Holling 2001).

The variables analyzed are soil, crops, and knowledge/technology. Soil formation is a slow and complex process (Stockmann et al. 2014); therefore, soil is a slowly changing variable. However, erosion events can be fast and lead to abrupt changes in the

Fig. 1. The adaptive cycles of agrarian soil use in time (modified from Holling [2001] and Gronenborn et al. [2014]).



variable concerning its further use (Auerswald et al. 2009). The anthropogenic colluvial deposits are used as archives of land use. The slowly changing variable crop affects the SES through the introduction of new crops, which is visible in archaeobotanical records (Table 1, organized chronologically from Neolithic to modern times). The variable knowledge/technology influences the SES through fast changes that are implemented by humans, and are traceable in the archaeological record.

Societal changes, environmental factors, or a combination of both can lead to disturbances of the SES, which result in a reorganization of the system. After the disturbance and release, the system is reorganized, and a new phase of exploitation starts.

The SES agrarian soil use underwent one adaptive cycle from the Neolithic transition to the Industrial Revolution (Fig. 1). Through the use of soil, and the introduction of crops and new agrarian tools during the Neolithic transition, people settled down and produced higher food quantities (Childe 1936, Holling et al. 2002*b*). The Industrial Revolution marks the beginning of a second adaptive cycle with the industrialization of agriculture and food production, which simultaneously changed society by increasing the workforce of the secondary and tertiary sector. In between those two r-phases, most of society practiced agriculture (Evans 2012). The main crops of Central Europe remained similar to the ones introduced during the Neolithic, with the exception of potato or maize, which were introduced after the "discovery" of the American continent during the K-phase (Hawkes and Francisco-Ortega 1993, Rösch 1998, Rebourg et al. 2003). Soil cultivation depended on human and animal labor. The technology improved from the spade to the ard to the plow during the r-phase. While there was a succession of agricultural improvements, this development is similar to the r- and K-specialists that settle in a new habitat, as described by Holling and Gunderson (2002). Furthermore, Fath et al. (2015) state that in social systems, many small-scale adaptive cycles occur during the r- and K-phase of a bigger adaptive cycle, resulting in a prolonged K-phase of continued development and influencing the interplay between fast-changing and slowly changing variables. Fath et al. (2015) introduced a refined concept, consisting of the r-, K-, K_{lim}-, Ω-, and α-stage, and applied that to business management. The r-stage has innovations and provides the possibility of testing the innovations, and the spirit is entrepreneurial. In the K-stage, knowledge on best practices exists, and the previously established standards are accepted. In the added K_{lim}-stage, crisis plans come into action, which need technologies and cooperation to implement them. In the Ω-stage, improvisation is important, and access to a minimum of resources is required, while new actors and new knowledge need to be accepted. In the subsequent α-stage, experimenting and development of prototypes is a key competence, which requires certain resources and a willingness to try new paths (Fath et al. 2015). If this is applied to the adaptive cycles of agrarian soil use, it can be shown that the r-phase of the first and the second adaptive cycle of agrarian soil use indeed was shaped by innovations and entrepreneurial or experimental spirit. In the following K-phases, the previously introduced innovations are accepted, and best practice methods develop; e.g., the development and continuous use of the plow throughout the millennia. The K_{lim}-stage could be represented by the development of motorized agrarian tools during industrialization to facilitate work and free the workforce for the growing industry. In the Ω-stage, the new machines were accepted, and in the α-stage, experimenting with the new technology occurred and new pathways of agrarian soil use were explored. Further, the development of new tools during the first adaptive cycle was accompanied by smaller adaptive cycles within the social system, which in turn prolonged the K-phase of the big adaptive cycle agrarian soil use. In the sections that follow, the terminology of Holling and Gunderson (2002) is used, excluding the K_{lim}-stage of Fath et al. (2015). However, there are references to the latter.

ANALYSIS OF THE SOCIAL-ECOLOGICAL SYSTEM AGRARIAN SOIL USE IN CENTRAL EUROPE

Beginning approximately 40,000–45,000 years ago, the anatomically modern humans replaced the Neanderthals in Europe (Mellars 2004, Pinhasi et al. 2012, Hublin 2015). When the ice shields retreated after the Late Glacial Maximum (Hughes and Gibbard 2015), a new α-phase of the ecological system started with plant species and fauna spreading into the now ice-free space (Holling and Gunderson 2002), where soil formation processes started (Terberger et al. 2004). The adaptive cycle was influenced by climatic changes, and different species occupied these areas during the Early Holocene, including hunter and gatherer populations (Bos 2001, Tinner and Lotter 2001, Crombé et al. 2011, Giesecke et al. 2011). During the Mesolithic, hunting and gathering was the subsistence form of life (Uerpmann 2007, Bailey and Spikins 2008, Tolksdorf et al. 2009, Prummel and Niekus 2011); the impact on the soil remained small. When humans settled down and developed agriculture, they increasingly influenced the adaptive cycles of local ecosystems, and the SES agrarian soil use began.

The r-phase of the adaptive cycle: the Neolithic transition in Central Europe

Agriculture and agrarian soil use spread from the Near East (Davison et al. 2006, Tresset and Vigne 2011). The time of the Neolithic transition varies throughout Europe (Ammerman and Cavalli-Sforza 1971, Gkiasta et al. 2003, Coward et al. 2008). Several approaches exist on how this transition took place; e.g., people practicing agriculture moving in (demic diffusion) or spreading of the agricultural idea (cultural diffusion) over the continent (Haak et al. 2005, Davison et al. 2006, Larson et al. 2007, Gronenborn and Petrasch 2010, Lemmen et al. 2011, Zvelebil et al. 2012, Brandt et al. 2015). Whether demic or cultural diffusion happened, with the Neolithic transition the SES agrarian soil use began. The Neolithic transition marks the onset of the reorganization (α-phase) and the start of the r-phase of the SES agrarian soil use in Central Europe (Fig. 1). The SES variable soil became important to the sedentary people. They cleared forests for timber, fuel, and fields, which changed the water and nutrient cycles, and influenced soil formation processes (Bork et al. 2006, Kaplan et al. 2009, Gerlach and Eckmeier 2012, Ellis et al. 2013). On slopes, the clearing of forests led to erosion and the subsequent formation of anthropogenic colluvial deposit in valleys and depressions along slopes (Leopold and Völkel 2007, Houben 2012, Mitusov et al. 2014). With the beginning of the Neolithic, an increase in slope deposits is visible in Central Europe (Dreibrodt et al. 2010*b*); e.g., at the Wetterau, Central Germany (Houben et al. 2013), and at Albersdorf, Northern Germany (Reiß et al. 2009). However, anthropogenic colluvial deposits dating to the Neolithic remain scarce, perhaps because erosion was not widespread or because they were redeposited (Zolitschka et al. 2003) or later soil formation processes altered them. However, erosion events are also traceable in lake sediments (e.g., at Lake Belau, Northern Germany), dating to the middle Neolithic (Dreibrodt et al. 2010*b*).

The SES variable crops emerged during the Neolithic (Table 1). Archaeobotanical analyses show a vegetation change with sedentariness (Rösch 1987). Most of the crops domesticated in the Near East arrived in Europe with the Linear Pottery Culture and the Funnel Beaker Culture (Bakels 2014). The crops grown were similar in all Central European regions (Coward et al. 2008), with einkorn, emmer, wheat, and barley being most common (Herbig 2009, Bogaard et al. 2011, Bogaard et al. 2013). Domesticated animals were also present in Central Europe (Doppler et al. 2015).

The knowledge/technology variable of the SES is indirectly visible in archaeological findings: near Cologne, an excavated well of the Linear Pottery Culture revealed a spade made out of sycamore that dates to 5057 BCE (Mueller 2015). The spade is one of the earliest finds concerning soil cultivation, with the Linear Pottery Culture being the initial phase of the Neolithic (5500–2200 BCE) in Central Europe (Price et al. 2001, Eggert and Samida 2013). Another well excavated at the Baltic Coast of Northern Germany revealed Middle Neolithic artifacts, and archaeobotanical studies indicate agricultural land use (Brozio et al. 2014). The well was used during the Funnel Beaker Culture (4100–2800 BCE), the first sedentary culture in Northern Germany (Kirleis et al. 2012, Brozio et al. 2014, Whitehouse and Kirleis 2014).

Soil quality and proximity to fresh water seem to have been relevant for the settlement of regions (Lüning 2000, Rösch et al. 2002, Zolitschka et al. 2003, Fries 2005, Davison et al. 2006, Banks et al. 2013, Brozio et al. 2014). During the Neolithic, the SES agrarian soil use was in the r-phase of exploitation by transforming the landscape to adjust it to the new human needs connected to sedentariness. The arrival of the crop plants, the development of tools, and the onset of erosion show the emergence of the SES agrarian soil use. However, Gronenborn et al. (2014) propose that during this phase of the general SES agrarian soil use, the Linear Pottery Culture underwent an entire adaptive cycle. This demonstrates that the adaptive cycle consists of different spatial and temporal scales that influence the system as a whole, and takes into account the smaller and faster cycles within social systems that influence the variables of a bigger adaptive cycle (Fath et al. 2015). The adaptive cycle of the Linear Pottery Culture had an influence on the SES agrarian soil use, but the changes within this cycle did not lead to an alteration of the SES itself.

After the Neolithic transition, the SES agrarian soil use remained in the r-phase through the Bronze and Iron Ages. Plow marks in the soil, excavated ards in northern Italy and East Frisia, and rock carvings in northern Italy and Sweden show new agricultural methods and tools (Schultz-Klinken 1981, Tegtmeier 1993, Egg and Pare 1995, Fries 1995, Behre 1998, Zich 1999). The use of metal started with the Bronze Age (2200–800 BC) and continued through the pre-Roman Iron Age (800–15 BC), which consists of the Hallstatt and the La Tène period (Eggert and Samida 2013). Main innovations were sickles during the Bronze Age and scythes during the Iron Age (Jockenhövel 1994, Egg and Pare 1995). The use of metal shows a technological development and an assumed increase in knowledge, which led to mining activities that exploited previously unused natural resources; e.g., in the Black Forest, southwest Germany (Gassmann et al. 2006). The change in the knowledge/technology variable is seen as a development from spade to ard to plow, which can be explained using the approach of Fath et al. (2015) that several small-scale adaptive cycles can affect the r- and K-phase of a bigger cycle. However, this knowledge did not develop due to agrarian soil use but was used in an agricultural context later: the late La Tène hoard of Bad Buchau-Kappel in South Germany shows the diversity of iron objects such as pliers, knives, sickles, and scythes (Jockenhövel 1993); tillage tools were not found. In the agriculturally important hoard in Urach, Southern Germany, plow-shares were also absent (Fries 1995). The ards of the type Døstrup, found in Denmark, were used during pre-Roman Iron Age for soils under tillage, while the Walle type ard was used to break up formerly unused soils (Fries 1995). The latter and Early Iron Age ard shares found in the Netherlands (Sanden 1994) point to similar tillage practices in the Bronze and Iron Ages. The results show that metallurgy developed but was not initially used for agricultural purposes. However, in the Bronze Age, cattle traction was established and used for pulling the ard or carts (Bartosiewicz 2013); e.g., facilitating soil cultivation.

The SES variable crops changed little from the Neolithic to the Bronze and Iron Ages (Table 1). However, the soil variable shows an increase in anthropogenic colluvial deposits at the beginning of the Bronze Age and again in the Iron Age (Dreibrodt et al. 2010*b*). Bronze Age anthropogenic colluvial deposits were found at Albersdorf, Northern Germany (Reiß et al. 2009), at the Frauenberg in Bavaria (Lang et al. 2003), and at the Wetterau, where colluviation also happened during the Early Iron Age (Houben et al. 2013). Turbidites in Black Forest lakes also began in the Bronze Age (Rösch and Tserendorj 2011). The reason for the increased anthropogenic colluviation could be due to more settlements or increased deforestation for fuel purposes for metallurgy.

Research on Celtic fields in the Netherlands indicates an intensive agricultural system in the late Iron Age, with shorter fallow periods, higher manuring intensity, and changes in tillage practices (Spek et al. 2003). The change in management practices and the development of the Celtic fields shows a further development of agriculture (Jankuhn 1977). However, we argue that the SES agrarian soil use remained in the r-phase of exploitation. According to the adaptive cycle proposed by Holling and Gunderson (2002), the creative destruction and reorganization is a fast process. In the archaeological record, in pedological studies, and in palynology, changes are observable. However, these changes are slow, happening over centuries rather than decades. They can be interpreted as tests of the new innovations, which are characteristic of the r-phase (Fath et al. 2015), with entrepreneurial spirit leading to evolving management practices using the innovations. The use of metal indicates a greater knowledge of metallurgy and facilitated work; e.g., bronze sickles and scythes for harvesting. However, the tools used for tillage probably remained similar to the ard found in Walle, East Frisia that dates to the Bronze Age, as the ard shares in the Netherlands suggest (Schultz-Klinken 1981, Sanden 1994, Behre 2000). The development of these tools can be seen as a smaller adaptive cycle that occurred in the SES metallurgy and affected the SES agrarian soil use.

Transition to the K-phase: conservation of agriculture in Central Europe

In Antiquity, knowledge concerning agriculture was written down and documented. Greek and Roman scholars wrote the first European literary works on agriculture. Among them were Hesiod's *Érga kaì hemérai*, Cato's *De agri cultura*, Varro's *Res rusticae*, and Columella's *De re rustica* (quoted from Winiwarter 2006). These works were written mainly for the owners of *latifundia*; i.e., large landowners (James et al. 2014). Columella described a test to determine soil fertility: after digging a hole, the dug soil was refilled. If the soil formed a mound, the soil was fertile; if the refill formed a hollow, the soil was poor (McNeill and Winiwarter 2004). This approach tests the aggregate stability of a soil, which depends on soil texture, soil organic matter, biological activity, and the mineral content of a soil. The texts show that the SES agrarian soil use moved toward the K- or conservation phase (Fig. 1), with changes within smaller and faster subsystems influencing the adaptive cycle (Fath et al. 2015). The traditions and land management practices were written down, and the importance of "good" practices was stressed. However, it is important to note that the knowledge documented in the literary works of the agrarian writers might not have been applied to agriculture north of the Alps (Deschler-Erb and Akeret 2011), which necessitates historical, archaeological, palynological, and pedological analyses to understand former land use changes.

During the Roman period, Central Europe underwent different developments. In the south and west, the Romans controlled the provinces *Germania inferior* and *superior* as well as *Raetia* (Ausbüttel 2011). The Roman influence led to the establishment of *villae rusticae*, Roman forts and towns (Heiligmann 1996, Wilson 2006). A *villa rustica* is an agrarian production center (Groot and Deschler-Erb 2015); for example, in Bavaria, Germany, the production area belonging to one villa was approximately 50 ha (Leopold et al. 2010). In present-day south Germany, *villae rusticae* were usually established along the Roman roads, which made new areas accessible (Humpert 1995, Kerig and Lechterbeck 2004, Fingerlin 2008). For the area north and east of the Limes, there are few written sources; e.g., Caesars *de bello gallico* or Ptolemaios *Geographike Hyphegesis* (Nüsse et al. 2011). It should be noted that those descriptions might reflect stereotypical depictions of "barbarians" (Erdrich 2001). The written sources show a Roman viewpoint, which is in itself valuable, but to understand the SES agrarian soil use and its adaptive cycle, we need to consider all variables. Therefore, interdisciplinary approaches are used, such as the study of the Vecht River valley, located in the present-day Dutch–German border area (van Beek and Groenewoudt 2011). Archaeobotanical analyses show a continuation of the crop variable (Table 1). In southwest Germany, spelt was the most common crop (Rösch 2009).

Analyses at Lake Belau in Schleswig-Holstein and Lake Holzmaar in Rhineland-Palatinate (Dreibrodt et al. 2010*b*) show the contrast in the soil variable between the two regions. While at Lake Belau soil erosion increased during pre-Roman Iron Age and decreased during the Roman period, which led to a slower input of material into the lake, the situation at Lake Holzmaar was different: the input of material during the period of the Roman Empire was greater than in the pre-Roman Iron Age (Dreibrodt et al. 2010*b*). Anthropogenic colluvial deposits dating to Roman times are also found at the Kaiserstuhl, southwest Germany (Mäckel et al. 2003). This shows how difficult it is to reconstruct general agricultural practices for Central Europe for that period. Furthermore, the increasing need for building material resulted in deforestation, with its maximum extent around 250 CE (Büntgen et al. 2011), which affected soil erosion processes.

Agricultural technology was developed during Roman times, which led, for example, to the use of iron in spades. In present-day Germany, spades are found that date to the 1st to 3rd centuries, and they were fully made of iron (Mueller 2015). In Gallic provinces, a plow with two small wheels, which was pulled by 4–6 oxen, was used (Schneider 2007). Virgil described the "Roman plow" around 1 CE, which had iron shares (Lal et al. 2007). The further development of existing tools and the existence of written sources concerning the agricultural practices indicate the K-phase where connectedness increases, including knowledge and technology needed for successful agriculture. The variable soil shows erosion and colluviation processes. However, agrarian soil use was still connected to animal and human power with similar tools. These tools have been improved, but no invention happened that altered the actual practice of agrarian soil use.

The K-phase continued during Medieval times (500–1500 CE), an epoch that comprised many different dynasties, and societal and regional developments (Fried 2009). In Medieval times, the texts of the Roman agricultural writers were still copied. Further, Isidore of Seville wrote a short encyclopedia, which discussed plowing sequence and manuring, and Walafrid Strabo wrote a poem about 24 garden plants (Winiwarter 2006). This shows that certain groups of people wanted to conserve and improve the knowledge of agricultural practices, which indicates the K-phase of the adaptive cycle. However, agricultural practices seem to have relied on traditional practices, which were not necessarily related to the documented knowledge (Dotterweich 2013).

It is suggested that rye became a crop plant during the Medieval period, even though traces of rye were found dating to the Neolithic (Behre 1992). The proportion of the different crops changes over time and from region to region, but the plants used are the ones introduced in the course of the Neolithic/Bronze/Iron Age/Roman Period (Table 1).

The soil variable was slowly treated differently because fertilization was part of agriculture during Medieval times (Behre 2000). Furthermore, the variables soil and knowledge/technology became interconnected. Plaggen-manuring was practiced in Northern Europe, and ridge and furrow was prevalent (Behre 1976, Blume and Leinweber 2004, Haasis-Berner 2012, van Mourik et al. 2012), traces of which are found in the landscape today. For plaggen-manuring, the topsoil of adjacent areas was cut and distributed on the agricultural fields, which led to the development of heath in the cutting areas and enabled the cultivation of winter rye on the fields (Pape 1970, Behre 2000). The ridge and furrow developed due to the change from the ard to the moldboard or heavy plow, which turned the soil in one direction toward the middle of the field, and permitted agriculture on heavy clay soils (Seidl 2006, Haasis-Berner 2012, Andersen et al. 2016). The microrelief of the ridge and furrow fields enabled agricultural success in dry and moist years. On the ridge, harvest was good even in years with a lot of rainfall, while the furrow provided enough water during a dry year (Linke 1979). The three field system, growing two crops alternating with fallow, also spread and is observable in the archaeobotanical record (Rösch et al. 1992).

Erosion and colluviation increased during Medieval times (Zolitschka et al. 2003, Dreibrodt et al. 2010*b*, Henkner et al. 2017). Mining activities led to rapid deforestation but also to new regulations prohibiting forest clearing in certain areas (Steuer 1993). Deforestation for agricultural purposes continued, which led to erosion and the formation of anthropogenic colluvial deposits; e.g., in southwestern Germany in the Kraichgau dating to 980–1330 CE (Kadereit et al. 2010), or in the Black Forest around the Krumpenschloß between the 9th and 15th century CE (Knopf et al. 2012). In the area of Göttingen, several refilled gullies were discovered in the 1950s (Bork 2006). Research suggests that in 1342, a heavy precipitation event in Central Europe caused erosion in the low mountain ranges that led to the formation of gullies, which were later refilled by pedosediments (Bork et al. 2006). This is supported by a study at the catchment of Lake Belau in Schleswig-Holstein (Dreibrodt 2005) and another study at the Wolfsgraben, Bavaria (Dotterweich et al. 2003, Schmitt et al. 2003). Investigations at the Frickenhauser See, Bavaria show that between 1000 and 1870 CE, intensive soil erosion took place (Enters et al. 2006). These archives, thus, show an intensification of land use. However, humans still practiced agriculture with the help of tools and animals used for traction; the SES agrarian soil use was not reconstructed as such but remained in the K-phase.

Soil erosion increased again during the 18th century (Dotterweich 2013), after a phase of land abandonment at the end of the Medieval times (Dreßler et al. 2006, Fraser 2011), which might have happened due to a combination of erosion, crop failure, and the plague. Extreme weather events were documented (Dreibrodt et al. 2010*b*); e.g., the flood of 1783/84 was reported in newspapers and letters, and was recorded by meteorological stations across Central Europe (Brázdil et al. 2010). Analyses of sedimentation rates of the river Rhine's catchment show increased sedimentation in floodplains and formation of anthropogenic colluvial deposits (Hoffmann et al. 2009).

During the 19th century, the scientific analysis of soil increased. Albrecht Daniel Thaer, Justus von Liebig, Charles Darwin, and Vasilii V. Dokuchaev wrote their important works on soils (Liebig 1841, Thaer 1880, Darwin 1890, Evtuhov 2006). Thaer focused on agriculture and the relevance of humus and crop rotation (Feller et al. 2003*b*). Liebig tried to develop a mineral fertilizer (Montgomery 2010). Darwin focused on the formation of humus and the importance of worms (Brown et al. 2003, Feller et al. 2003*a*, Feller et al. 2006, Brevik and Hartemink 2010). Dokuchaev introduced the soil profile, dividing it into A-, B-, and C-horizons, and stressed that soils should be seen as an independent research object (Evtuhov 2006, Brevik and Hartemink 2010). These works show that the variable soil had become a research topic. The variable knowledge was increasingly interlinked with practical soil use, at least considering the landowners, not necessarily the peasants. The increasing knowledge eventually led to the development of new tools, which resulted in the creative destruction and reorganization of the SES agrarian soil use.

The Ω- and α-phase of the social-ecological system agrarian soil use and the beginning of a new cycle

With industrialization, the SES agrarian soil use moved through the Ω-phase of creative destruction and the α-phase of reorganization (Fig. 1). The different variables changed considerably.

A change in the knowledge/technology variable is observable in new machines, but also resulted in global societal changes. Technological advances, such as the invention of the steam engine, led to motorization and mechanization of agricultural practices (Bergmann 1970, Gessner 1976, Hahn 2011). The machine manufacturer Fowler invented the plowing engine (Seidl 2006), and the blacksmith John Deere marketed a plow that grew in importance with the invention of the tractor (Lal et al. 2007). Increasing knowledge and technology led to new fertilizers. Industrialized nitrogen production using the Haber-Bosch technology increased cereal yield in Germany between 1918 and 1938 by approximately 50% (Niedertscheider et al. 2014). These developments were closely connected to the use of fossil fuels (Schumacher 1993). The use of new technologies changed the strong link between agriculture and animal husbandry because animals were no longer needed for traction and manure (Lambin et al. 2001). Traditional crop rotation practices and fallow were also abandoned due to cheap nitrogen availability (Montgomery 2010). This development marks the r-phase of exploitation, where growth is accomplished with new efficient technologies. The innovations are tested and entrepreneurial spirit dominates, as proposed by Fath et al. (2015). It also starts the process toward a knowledge-based society, which influenced the agricultural sector (Uekoetter 2012), and raised the workforce in the secondary and tertiary sector (Hahn 2011), which led additionally to urbanization (Antrop 2004) and globalization (Robertson 1992, Levitt 1999). The global trade involves among others, food, fertilizer, fodder, and raw material needed for agriculture and agrarian technology. Information exchange is enabled by the internet and relatively cheap transportation. This global development means that we can no longer consider regional practices when analyzing the SES agrarian soil use.

The SES variable crop changed with the introduction of genetically modified organisms and the widespread use of pesticides, herbicides, and fungicides. Fewer crop plants are used in agriculture today. The crops variable is closely related to the knowledge variable of society because genetically modified organisms developed through human interference (Tiedje et al. 1989, Anklam et al. 2002). Furthermore, society today depends on few crops, namely wheat, rice, and maize (Cassman 1999); e.g., *Triticum aestivum* became the dominant crop in the 1920s in southwest Germany (Rösch et al. 1992). Monocultures of such crops are a new phenomenon; e.g., rice (Shen et al. 2004).

The soil variable is still prone to erosion but also to other forms of degradation, such as compaction and nutrient depletion. Soil erosion increased with changes in plowing intensities due to bigger and more powerful machines, and heavy machinery enhances soil compaction (Lal et al. 2007). In Europe, an erosion rate of more than 1 t ha^{-1} y^{-1} is regarded as unsustainable (Verheijen et al. 2009). Today, erosion in Europe ranges between 3 and 40 t ha^{-1} y^{-1}, which is impairing the soil's productivity and is becoming more important as the global population grows (Verheijen et al. 2009).

Another soil-related aspect of the new adaptive cycle is the increase in global fertilizer use by 700% in the last 40 years (Foley et al. 2005), which has led to changes in the nitrogen and phosphorus cycles (Smil 1999, 2000). While nitrogen can be generated using the Haber-Bosch method, most of the phosphorus used in agriculture is of phosphate rock origin and is nonrenewable. The mining of these reserves, mostly in China, the United States, and Morocco, has tripled since World War II (Cordell et al. 2009), and there was a global increase of 20% in phosphorus fertilizer use between 2000 and 2008 (MacDonald et al. 2011). Losses of phosphorus and nitrogen affect off-site ecosystems (e.g., eutrophication of lakes and marine ecosystems) and influence global warming and biodiversity; e.g., through N_2O, NO, NO_3, and NH_3 (Tilman et al. 2002, Lal et al. 2011). The carbon cycle also changed with the dependency on fossil fuels, which led to an increase in atmospheric greenhouse gases from 280 ppm CO_2-equivalent at the beginning of industrialization to 430 ppm in 2005 (Falkowski et al. 2000, Aertsens et al. 2013). Present fertilizer production relies on fossil fuels and contributes to CO_2 emissions, as does the use of agricultural machinery, land use change in the form of deforestation, and fertilization (Canadell et al. 2007, West et al. 2010).

The dependence on fossil fuels indicates a growing rigidity of the SES, which would point toward the end of the K-phase of the adaptive cycle. However, innovative concepts combine the use of new technology and knowledge with alternative or traditional agricultural practices; e.g., carbon sequestration in soils. Agroforestry, hedgerows, low or no tillage, and cover crops affect erosion, biodiversity, nutrient leaching, soil organic matter, and carbon sequestration (Aertsens et al. 2013). This points toward the small and fast adaptive cycles influencing the big adaptive cycle agrarian soil use and exploring alternative pathways to the challenges of the present. However, the global cropland under no-till is only 9% (Lal 2013). In present-day Germany, no-tillage is practiced on 1463 km², equaling 1.3% of the land base, while conservation or conventional tillage is used on 11,0775 km² (Statistisches Bundesamt 2016). This shows that even in a highly industrialized country, with rapidly increasing knowledge, no-till is practiced by only a few. This supports the suggestion that we are in the K-phase of conservation because most agrarian soil use depends on mineral fertilizers and tillage practices with big machinery. Whether a new Ω-phase is approaching depends on today's decisions. These rely on studies conducted by different scientists; e.g., concerning the functioning of the nitrogen cycle. A long-term field study in France showed that cover crops reduced nitrogen leaching, while no-till did not result in significant nitrogen sequestration (Constantin et al. 2010). A study in New Zealand showed that the effectiveness of cover crops in preventing nitrogen leaching depended on sowing dates and soil type, and was influenced by weather variability (Teixeira et al. 2016). The results suggest that site-specific practices and holistic management approaches are necessary to develop the agricultural sector toward more sustainability. However, interdisciplinary approaches are needed to communicate these new findings to soil users and society in general, which might also pave the way to greater food security and equality worldwide (Godfray et al. 2010, Lal et al. 2011, Altieri 2012, Scholten 2014). Further, the development in the social component of the SES needs to be investigated in order to determine the effect of small and fast adaptive cycles on the big adaptive cycle of the SES agrarian soil use.

CONCLUSION

The adaptive cycle narrative is useful for examining the changes occurring in a social-ecological system, such as the changes in the agrarian soil use SES over the last millennia. The narrative helps in understanding changes of the SES and within the SES over time, while focusing on important variables, in the presented case, soil, crops, and knowledge/technology. This approach could also be important for archaeological and soil scientific research in general because the concept of SESs and adaptive cycles can be applied to broader developments within social-ecological systems, as shown in this study. It might also be used to connect individual case studies to international contexts.

The adaptive cycle of the SES agrarian soil use started with the Neolithic transition and sedentariness. During the Neolithic, and the Bronze and Iron Ages, the adaptive cycle was in the r-phase. Innovative tools and ideas developed, which enabled the societies to successfully practice agriculture. With Antiquity, the SES moved into the K-phase, where the knowledge concerning agricultural practices was documented by written sources and best practice methods were determined. During Medieval and modern times, the general knowledge, and agricultural knowledge in particular, increased. Furthermore, agricultural tools were improved by, for example, using iron in plow shares, thus incorporating the adaptive cycle of the SES metallurgy. With industrialization, the SES moved through the Ω-phase of release or creative destruction and the α-phase of reorganization. The SES changed considerably with the α-phase, which led to a separation of animal husbandry and arable farming and a new r-phase after the mechanization of agriculture. This is comparable to the establishment of agriculture in the Neolithic due to the big innovations that changed the SES. The Neolithic transition led to sedentariness, so that first settlements and probably new societal structures developed. The Industrial Revolution enabled a diversified society with more people working outside the agrarian business due to the innovations of the r-phase. The knowledge and technology variable are interconnected in both r-phases; e.g., in the development of the plow and the Haber-Bosch method. After industrialization and mechanization, agrarian soil use no longer involved the work of animals and humans, but work of machines. This has new consequences for the soil variable, comparable to the consequences of deforestation, which subjected the soil to erosion after the establishment of fields since the Neolithic. The new impact on soil includes compaction, nutrient depletion, and other forms of soil degradation. The crops used in agriculture were first introduced in the Neolithic. They were used in different proportions during the last millennia. With industrialization, new genetically modified organisms were developed, thereby connecting the variables crop and knowledge/technology. The crop variable underwent another change, as society depends on a limited variety of crop plants for nutrition today.

A difference between the two adaptive cycles is the speed of the transition from r- to K-phase, which lasted several millennia in the first cycle but happened in the course of decades in the second. The increasing knowledge of the first K-phase, which started with the Greek and Roman agricultural writers and culminated among others with Thaer, Liebig, and Darwin, eventually had a vast effect on surplus production and technological development that resulted in a reorganization of the SES and the second adaptive cycle. The knowledge is still increasing steadily, and technological development has led to a high-tech agribusiness that depends on computers, GIS, fertilizers, and more. These new developments also affect the soil and crops used. To investigate these effects, interdisciplinary work is needed to ensure the resilience of the SES agrarian soil use without detrimental effects on soil, crops, knowledge/technology, and climate. These interdisciplinary studies should include various disciplines, among others, soil science, sociology, anthropology, climatology but also history and archaeology, to understand the past developments of and within a region. The SES and adaptive cycle could be used to structure the research in advance due to the focus on specific variables, while also including the systems approach and acknowledging the connection between natural and social systems. Further challenges for these studies are that small-scale and fast adaptive cycles in the social system need to be investigated to understand the development of the big cycle of agrarian soil use. As we are in the K-phase of the adaptive cycle, small and fast adaptive cycles in the social system will determine how long the system remains in the present phase. If innovations and traditions are combined and lessons from the past (e.g., concerning erosion) are learned, the new K-phase might last for an extended time. However, if this does not happen, a new Ω-phase might result in a reorganization of the system with an unknown outcome. The variety of possible responses to global, regional, and local challenges requires scientists from different fields to investigate the different variables of the SES agrarian soil use to understand the processes and interactions between and within the variables. This might contribute to the resilience of the SES and lead to new policies on a global scale. Interdisciplinary research helped us understand the adaptive cycle of the SES from the Neolithic to industrialization. It is also necessary to develop a resilient agrarian soil use for the future.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9729

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