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Nutrient recycling and soil fertility management in the course of the industrial transition of traditional, organic agriculture: The case of Bruck estate, 1787–1906

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ABSTRACT

Late 18th century agriculture was under social and economic pressures, emanating from unprecedented population growth and establishing world markets. Farmers met these challenges successfully and largely without external energy subsidies and mineral fertilizers. Our research asks (1) if and how performance gains were achieved by improving traditional nutrient management through advanced, organic farming and (2) whether this early agrarian intensification compromised the natural capital of agro-ecosystems.

We present a long-term socio-ecological perspective on nutrient cycling in the historical agro-ecosystem of the estate Bruck in eastern Austria, from 1787 to 1906. Focal point is the development of different patterns in nutrient cycling, tracing the transition from traditional, organic to industrial farming. We used nutrient balances and input-output analysis for a quantitative assessment of nitrogen and phosphorus flows. To investigate the correlation between growing system performance and improved internal nutrient cycling, we applied the Finn cycling index (FCI), which represents the fraction of nutrients recycled on-farm before leaving the system. Improving nutrient cycling entailed the operational integration of livestock, the utilization of ecological nutrient replenishment processes through legume intercropping and optimizing nutrient transfers from extensive land-use systems. Nitrogen recycling grew steadily from 20% in 1787 to 36% in 1906. Phosphorus recycled on farm grew accordingly from 33% in 1787 to 46% in 1840, before dropping to 31% in 1906 due to increased application of mineral fertilizers. We show, that cereal yields more than doubled through improved traditional nutrient management. In the long-run, however, advanced organic farming induced an unsustainable use of phosphorus and the loss of ecological buffer capacity from traditional mixed land-use systems.

1. Introduction

Agro-ecosystems today are under mounting pressure, as the demand for food and energy is increasing (Krausmann et al., 2013; Reeves, 1999). It has been argued that agriculture requires a transition that is both economically viable and environmentally sound, to manage the challenge of future food security without compromising the sustainable functioning of agro-ecosystems (Foley et al., 2011; Godfray and Garnett, 2014). Among the many pathways for sustainable agricultural intensification, integrated nutrient management (INM) holds great promise to close yield gaps and minimize environmental hazards without further expanding agricultural land (FAO, 2006; Mueller et al., 2012; Tittonell, 2014). In addition to modern technologies, INM also builds on traditional methods of nutrient management and organic nutrient sources, most importantly manure (Chadwick et al., 2015; Wu and Ma, 2015).

Here, we offer a long-term socio-ecological perspective on agricultural intensification in Central Europe under conditions of growing demand for food and feed from the 18th to the 20th century. We investigate practices of traditional nutrient management in a pre-industrial crop-livestock system in Austria. Traditional nutrient management combined agro-ecological strategies like the utilization of ecological soil replenishment processes through ecosystem diversification, internal nutrient recycling, and the application of biological fertilizers (Kremen and Miles, 2012). Traditional, organic methods are promoted by agro-ecologists and aimed for by INM, due to their potential for ecological intensification and the merits of a sustainable use of soil resources (Altieri, 2004; Fonte et al., 2012).

Prior research led to the conclusion that soil fertility was a bottleneck for the intensification of pre-industrial European agro-ecosystems, before industrial fertilizers became available (Krausmann et al., 2008a,b). Pressure on European farming systems rose with a rapidly

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growing population, urbanization, and the emergence of international markets since at least the late 18th century (Federico, 2009). Pre-industrial agriculture in Europe did, however, experience a marked rise in land and labor productivity, owing largely to advanced organic farming techniques originating from the agricultural revolution in pre-industrial England (Allen, 2000). This research explores the evolution of different patterns in on-farm nutrient cycling induced by improvements in traditional nutrient management from the late 18th to the early 20th century. It has remained an issue of debate, how the optimization of agro-ecological nutrient flows and innovations in organic farm management contributed to productive performance gains (Allen, 2008). Likewise, the implications for the sustainability of the agro-ecosystem's nutrient cycle have not been investigated.

What are the synergies, trade-offs of human interventions in the nutrient cycle? How did farmers sustain the performance of agroecosystems, i.e. their economic productivity and maintain an equilibrium state of nutrients? Which strategies were adopted to increase performance? Were these strategies successful in the long-run, or did they cause disturbances in system functioning? Trying to answer these questions, we also investigate whether farmers could buffer imbalances in either the social or ecological domain and at which point moving from organic to industrial production became inevitable.

Our case study deals with a farming estate in eastern Austria. The estate of *Bruck* maintained a detailed documentation of its farming operation from its 16th century origins of the agricultural demesne to its present-day agribusiness set-up. We apply a long term socio-ecological research approach (LTSER), (Haberl et al., 2006) to investigate the changes in farming and nutrient systems of the estate from 1787 to 1906. The core element of the assessment of traditional soil fertility management are mass balances and flow analyses of nitrogen (N) and phosphorus (P). The supply of these essential plant nutrients was crucial for maintaining and improving system performance.

This approach allows to create a set of indicators of nutrient flow accounting, which are used to demonstrate how improving internal nutrient (re-)cycling correlates with productivity increases in pre-industrial agriculture and to explore the inadvertent side effects of advanced organic farm management on soil fertility and the agricultural landscape. We will discuss how the estate responded to the loss of the resilience of the agro-ecosystem's nutrient cycle and its growing vulnerability towards economic pressures. The paper depicts agricultural modernization as a dynamic process of adaptation to uncertainties and risks rising from human interventions in ecosystem processes. In light of the contemporary discussion on food security, lessons from these historical experiences in responding to universal challenges of agriculture can be used to discuss the potential of traditional nutrient management as a viable pathway for agriculture's future sustainable intensification.

2. Conceptual approach

All human societies maintain biophysical exchange processes with the environment, thereby creating socio-ecological systems "in which fundamental patterns and processes are co-regulated by socio-economic and ecological processes" (Haberl et al., 2011). The assemblage of coupled ecological and socio-economic flows of energy, materials and substances has been denoted as socio-ecological metabolism (Gaube and Haberl, 2013). The metabolism of pre-industrial societies hinged on biomass as the sole energetic basis (Fischer-Kowalski and Haberl, 2007). A carefully managed balance between different intensive and extensive land-uses was necessary to provide the energy for food, processing, and forage, without overusing these resources. González de Molina (2010) defined a number of perturbations destabilizing the metabolism of agrarian societies. These were deforestation (lack of fuel), erosion and soil degradation (land shortage), and most importantly, the depletion of soil fertility.

Large scale consumption of fossil energy and artificial fertilizers in the 20th century alleviated the biophysical constraints of pre-industrial societies, and diminished the economic side effects of environmental degradation, thereby facilitating socio-economic growth and new patterns of material and land-use (Krausmann, 2001). We argue, however, that agricultural growth from the late 18th century onwards was accomplished within the energetic limitations of agrarian societies through improved ecosystem management. Tello et al. (2006) studied the energy system of 19th century farming communities. The authors found that an increase in biomass and energy output was achieved without external energy subsidies. A number of novel intensification strategies helped establish an *advanced organic economy* (AOE) (cf.) Wrigley (2006).

The process of agrarian intensification since the 18th century is often referred to as 'agricultural revolution'. Historians agree about the pivotal role of the agricultural revolution for industrialization (Overton, 1996), but the roots and driving forces of the 'revolution' remain an issue of debate among agricultural historians (Kopsidis, 2006). The modernization of farming was fostered by innovations in science, technology and the advent of entrepreneurial farming (Shiel, 1991). With respect to the transformation of the nutrient system the trajectory of the revolution may be divided into two transitional phases or two agricultural revolutions.

Prior to the 'revolution' farming in temperate Europe was based on animal-drawn crop cultivation in a biannual or triennial rotation system with long fallows (Mazoyer and Roudart, 2006). The first agricultural revolution was driven by the rise of agronomy as a scientific discipline. A novel, rational approach fostered the development of an *advanced organic agriculture*, with integrated crop-livestock management (Gliessman, 2007). The new mode of integrated farming—also known as convertible husbandry or high farming—harnessed synergies by incorporating intensive livestock keeping into farm operations. Agroecosystem diversification with forage and break crops introduced new crop rotation patterns, replacing the old fallowing system.

The advanced organic economies doubled agricultural land and labor productivity, nurturing the industrial revolution, which triggered a second agricultural revolution (Mazoyer and Roudart, 2006). Mechanization brought the diffusion of new metal tools as well as steam engines for threshing and later, ploughing. Steam powered engines revolutionized transportation, removing an energetic bottleneck for growth in pre-industrial societies, by providing mineral fertilizers and organic amendments from distant environments for agriculture (Fischer-Kowalski et al., 2013; Smil, 2001).

The entailed estate Bruck was gradually modernized from the late 18th to the early 20th century, providing a model case of the outlined evolution of agro-ecosystems. Five points in time have been chosen as representations of the traditional, organic (1787), advanced organic (1820 and 1840) and early industrialized (1881 and 1906) mode of production.

3. Study area

Bruck estate is situated some 70 kilometers southeast of Vienna, in the *Brucker Gate*, a lowland passage between two mountain ridges in the border region between Austria and Hungary. The lowland composes of a gravel terrace deposited by the River Danube, which is intersected by the river *Leitha* flowing through in an eastward direction. The river roughly marks the junction between the Vienna Basin in the northwest, a hilly terrace covered with Aeolian silt deposits, and the Small Hungarian Plain, a Pannonian steppe landscape covered by Aeolian sand to the southeast.

The agricultural estate Bruck originated in the Manor Bruck, which stretched on both sides of the Leitha river and consisted of three communities. The city of *Bruck an der Leitha* occupied all the manor's Austrian territory north of the river with some land extending south into Hungary. The villages *Parndorf* and *Neudorf* reside on the so-called *Parndorf Heath* (ger. *Parndorfer Heide*) a sweeping, treeless grassland steppe.