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Scientific case studies in land-use driven soil erosion in the central United States: Why soil potential and risk concepts should be included in the principles of soil health

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ABSTRACT

Despite recent improvements in overall soil health gained through conservation agriculture, which has become a global priority in agricultural systems, soil and water-related externalities (e.g., wind and water erosion) continue to persist or worsen. Using an inductive, systems approach, we tested the hypothesis that such externalities persist due to expansion of cultivation onto areas unsuitable for sustained production. To test this hypothesis, a variety of data sources and analyses were used to uncover the land and water resource dynamics underlying noteworthy cases of soil erosion (either wind or water) and hydrological effects (e.g., flooding, shifting hydrographs) throughout the central United States. Given the evidence, we failed to reject the hypothesis that cultivation expansion is contributing to increased soil and water externalities, since significant increases in cultivation on soils with severe erosion limitations were observed everywhere the externalities were documented. We discuss the case study results in terms of land use incentives (e.g., policy, economic, and biophysical), developing concepts of soil security, and ways to utilize case studies such as those presented to better communicate the value of soil and water resource conservation. Incorporating the tenets of soil potential and soil risk into soil health evaluations and cultivation decision-making is needed to better match the soil resource with land use and help avoid more extreme soil and water-related externalities.

1. Introduction

Improving soil health in agricultural systems has become a major priority in recent years, especially given the growing awareness of the role of soil in controlling Earth cycles (hydrological, geochemical, etc.) and the ecosystem goods and services supported and regulated by soil. These ecosystem goods and services (e.g., provision of food and raw materials, biodiversity habitat, recycling wastes and filtering water, mitigating flood and pestilence risks, cultural and heritage values, etc.) place soil in a critical position to achieving international development goals (Keesstra, S. D., et al., 2016; Mol and Keestra, 2012). Promoted strategies to improve soil health, and therefore soil ecosystem goods and services, have included conservation agriculture practices such as no- or reduced tillage, diversifying crop rotations, maintaining high levels of crop residue between plantings, incorporating diverse cover crops into crop rotations and integrating livestock into cropping systems (Dumanski, Peiretti, Benetis, McGarry, & Pieri, 2006; Hobbs, 2007; Pittelkow et al., 2015). Soil health enhancement has improved agricultural productivity while simultaneously promoted soil-related ecosystem goods and

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services, such as carbon sequestration via organic matter accumulation or water regulation via infiltration and storage (Doran, 2002; Koch et al., 2013; Lal, 2004).

Despite recent gains in overall soil health, concerns over soil erosion, watershed runoff volumes, and water quality have escalated as landowners and scientists have observed near catastrophic watershed-scale soil and water-related externalities (Koch et al., 2013; McBratney, Field, & Kock, 2014) as well as persistent anthropogenic-related increases in soil erosion over time (Montgomery, 2007a). Externalities are defined as consequences or side effects of one activity that are not reflected in the true cost of the good or service being produced and where the side effects create costs to a party who did not participate in the original activity (Buchanan & Stubblebine, 1962; Lafont, 2008). Examples of soil and water-related externalities include erosion by wind or water, water quality degradation due to sediment or nutrient loading, and shifts in runoff and stream flow dynamics that may increase severity of events such as flooding. These issues are of particular interest to stakeholders throughout the central United States' Great Plains, where soil and climate characteristics have historically limited row crop production potential and where large-scale expansion of cultivation has created or contributed to externalities of historical significance (e.g., the 1930s Dust Bowl; Montgomery, 2007b). Likewise, these issues are also of interest to stakeholders globally, in diverse climate, soil, and management contexts (e.g., see Keesstra, S. et al., 2016; Kirchhoff, Rodrigo Comino, Seeger, & Ries, 2017; Parras-Alcantara et al., 2016; Rodrigo-Comino et al., 2016).

Soil scientists have globally recognized these issues and have therefore developed the concept of soil security (Koch et al., 2013; McBratney et al., 2014). Soil security recognizes the integral role that soil has in meeting today's global challenges (e.g., food security, water security, climate change abatement, ecosystem services provision, etc.). To insure soil contributes to overcoming these challenges, the dimensions of soil security must be further developed, understood, and promoted. These dimensions include: *capability* (what functions can a given soil perform, and in doing so, produce?), *condition* (what is the current state of a given soil compared to its reference condition?), *capital* (what are the economic values produced by various services supported by soil?), *connectivity* (do managers have the right knowledge and resources to manage the soil according to its capability?), and *codification* (are policy decisions including appropriate stakeholders who can translate codified soil science knowledge into more effective policy solutions?) (A full treatment of these dimensions is provided in McBratney et al. (2014)). Clearly, soil health and soil potential and risk are important characteristics of these dimensions, since soil health improvements may be driven by enhanced *connectivity* and should produce benefits in *capability*, *condition*, and *capital*, while soil potential/risk create variability in *conditions* (i.e., diversity of reference states) and are important for *codification* of environmental policies (e.g., land resting programs such as the U.S. Conservation Reserve Program aimed at limiting soil externalities by respecting inherent soil limitations).

For various reasons, including, but not limited to, disparate data sources or data availability, intensive and difficult modeling efforts, and limited resources or time, a paucity of watershed-scale or individual farm level research regarding land use driven soil externalities exists. Rather than investigating the systemic root causes potentially driving soil-related externalities, emphasis has remained on correcting or mitigating existing soil problems, primarily at the field level, through improving soil health. Unfortunately, soil-related environmental externalities, namely, wind and water erosion, continue to persist or are getting worse at watershed and landscape scales, which may threaten the function of provisioning, regulating, and supporting ecosystem goods and services (Keesstra, S. D., et al., 2016) that these agricultural systems provide in the long term.

We propose that there are at least three hypotheses that explain why soil externalities persist despite wide-scale prioritization of and evidential gains in soil health by conservation agriculture practices:

Hypothesis 1:. Soil externalities persist because of time-delays needed for soil improvement to take effect after the implementation of conservation agriculture practices;

Hypothesis 2:. Soil externalities persist because of the slow adoption of conservation agriculture practices by land managers;

Hypothesis 3:. Soil externalities persist due to the expansion of cultivation onto areas unsuitable for sustained agricultural production.

For Hypothesis 1, much work has been done to understand the short- and long-term dynamics of soil health and soil ecosystems arising from improved soil management practices (Doran, 2002; Hou, Ouyang, Maxim, Wilson, & Kuzyakov, 2016; Liu et al., 2013; Pikul et al., 2009). For Hypothesis 2, recent evidence suggests that, although variable by U.S. region, adoption of conservation agriculture practices remains low relative to soil health goals (Wade, Claassen, & Wallander, 2015). The purpose of this paper, therefore, is to test Hypothesis 3 using an inductive, systems approach, which takes an integrative rather than reductionist perspective to document noteworthy cases of soil externalities and the underlying land and watershed dynamics that led to their occurrence. To test our hypothesis (statistically stated as H_0: cultivated land area pre-externality = cultivated land area post-externality, H_a: cultivated land area pre-externality ≠ cultivated land area post-externality), we utilized a variety of data sources and analyses to uncover the dynamics unfolding in the respective watersheds or regions where they occurred. The goal of this paper is to then to use these case studies to illustrate, with both quantitative data and visual photographic evidence, the important linkages between soil health and soil potential/risk. In this way, we aim to improve our ability to communicate the value of soil and water conservation and provide valuable information useful for guiding future research and policy efforts around the topics of soil health and soil security.

Before proceeding to the case studies, we first provide a brief review of recent cultivation expansion and the physical processes related to soil erosion and soil health improvement. We then describe the general materials and methodology used to develop each case study, which are organized and presented in sections for wind erosion, water erosion, and hydrologic regime changes. In each specific case a more detailed description of the data and analyses employed to document the externality of interest are provided. Lastly, we present a brief discussion on: 1) what we may learn from the case studies presented; 2) creating a tighter coupling between the concepts of soil potential and risk with soil health, particularly in the light of recent prioritizations surrounding overall soil health; and 3) improving our ability to communicate the consequences to soil and water resources of accelerated expansion of cultivation area.

2. Brief reviews in cultivation expansion and soil processes[1]

2.1. Dynamics of cultivation expansion

Recent land use changes include large shifts away from native or conservation grasslands [e.g. Conservation Reserve Program

[1] Due to space constraints we only provide high level summaries of these issues. Readers are encouraged to utilize the literature cited here if interested in more detail.