Title

Endogenizing soil ecosystem feedback in agricultural innovation adoption

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Abstract

Current models of agricultural technology adoption focus primarily on economic and social factors while treating soil as a static resource. This conceptual paper proposes a conceptual model that endogenizes soil ecosystem within innovation adoption processes. Integrating soil ecosystem through a simplified soil organic matter model with a socio-economic systems, we present a conceptual model linking soil ecosystem changes to farmer decision-making through feedback mechanisms. The model addresses the gap between existing adoption models by incorporating a bidirectional relationship between management practices and soil health. Using conservation tillage adoption as an illustrative case, we conceptualize how soil organic matter accumulation, erosion control, and nutrient cycling create delayed benefits that influence farmer consideration perceptions and adoption decisions. This approach extends traditional diffusion models by recognizing soil as an endogenous system component rather than a passive production input or a medium which accumulates impacts, providing a foundation for future empirical research on sustainable agricultural practice adoption.

Keywords: agricultural innovation, soil ecosystem services, technology adoption, conservation tillage

1. Introduction

Sustainable agricultural practices offer significant environmental and economic benefits, yet their adoption remains slow despite apparent agronomic advantages for farmers (Conti et al., 2021). Current understanding of agricultural innovation adoption relies on models that emphasize economic incentives, social networks, and policy interventions while treating soil as a static production factor (Adamsone-Fiskovica & Grivins, 2024). This approach disregards that many soil management practices influence soil ecosystem functions, creating either delayed benefits or degrading soil, which can in turn influence long-term adoption decisions.

The problem becomes particularly acute when examining practices like conservation tillage where the primary mechanism of benefit delivery operates through gradual soil ecosystem improvements. Traditional adoption models struggle to capture these delayed, soil-mediated benefits because they lack explicit representation of soil as a dynamic system component (Turner, 2021).

This paper proposes a conceptual model that endogenizes soil ecosystem feedback within agricultural innovation adoption models. By treating soil as an endogenous system component that both responds to and influences farmer decision-making, we address what Turner (2021) identifies as a critical gap in linking soil complexity with socio-economic considerations in agricultural systems.

The model builds upon established diffusion theory (Rogers, 2003) and system dynamics approaches to technology adoption (Struben & Sterman, 2008; Derwisch et al., 2016) while incorporating soil ecosystem dynamics as a core driver of adoption processes. This integration is particularly relevant for understanding ecological intensification practices (Tittonell, 2014) that derive their benefits primarily through soil health improvements rather than external inputs.

2. Technology adoption in agriculture

Agricultural innovation adoption has been extensively studied through multiple theoretical lenses. Rogers' (2003) diffusion of innovations theory identifies five key innovation attributes affecting adoption rates: relative advantage, compatibility, complexity, trialability, and observability. Relative advantage, however, may only become apparent decades after implementation due to the delay that soil management practices have in improving soil ecosystems. Soil provides multiple ecosystem services relevant to agricultural production including nutrient cycling, water regulation, erosion control, and carbon storage (Paul et al., 2021). These services respond dynamically to management practices, with improvement or degradation occurring over months to decades depending on the specific service and environmental conditions.

Bio-economic models, which attempt to explain technology adoption focus on profit maximization and risk considerations (Finger, 2012). These models explain substitution decisions but lack an explanatory potential where benefits accrue slowly through ecosystem processes. Temporal dynamics between adoption decisions and their costs and the benefits which may occur in the future via ecosystem benefits are delayed in a system which is readily captured in economic frameworks. Technology adoption delays and capturing feedback effects are particular problems that are well suited for System Dynamics approaches. In a case on electric vehicle adoption Struben and Sterman (2008) show how social exposure and the development of infrastructure lead to reinforcing loops in the alternative fuel vehicle adoption. The diffusion process of different types of seeds for agricultural production is shown by Derwisch et al. (2016), based on an understanding on perceived utility and social learning.

Derwisch et al. (2016) in their model treat production outcomes as immediate (with a short delay) consequences of practice changes. This assumption works well for technologies like improved seeds or fertilizers, where benefits are observable within a single growing season. For soil status or soil health status-based practices, this assumption needs to involve longer time delays, because the mechanism generating benefits operates through slow soil ecosystem processes.

For that reason, we have chosen a practice, Conservation tillage, which requires an endogenization of the soil ecosystem into traditional adoption models. Conservation tillage, despite clear long-term benefits including reduced erosion, improved water retention, and lower input costs, adoption remains limited in many regions (Kassam et al., 2022). Farmers name various barriers including equipment costs, weed management challenges, and uncertainty about yield impacts (Paye et al., 2024). However, these barriers may mask a deeper issue: the temporal disconnect between practice adoption and benefit realization through soil ecosystem improvements. When benefits depend on soil organic matter accumulation or biological activity enhancement, farmers must wait years to experience the full advantages that make adoption economically attractive (Turner, 2021). The challenge for adoption modeling lies in connecting these slowly-changing ecosystem services to farmer decision-making processes that operate on seasonal or annual timescales. Farmers must make planting, tillage, and input decisions based on current conditions while the ecosystem services that justify sustainable practices may not fully manifest for years.

3. Conceptual model

The proposed conceptual model addresses the temporal mismatch between adoption decisions and ecosystem service delivery by explicitly modeling soil as a dynamic system component that mediates the relationship between management practices and agricultural outcomes. Figure 1 illustrates the core conceptual structure.

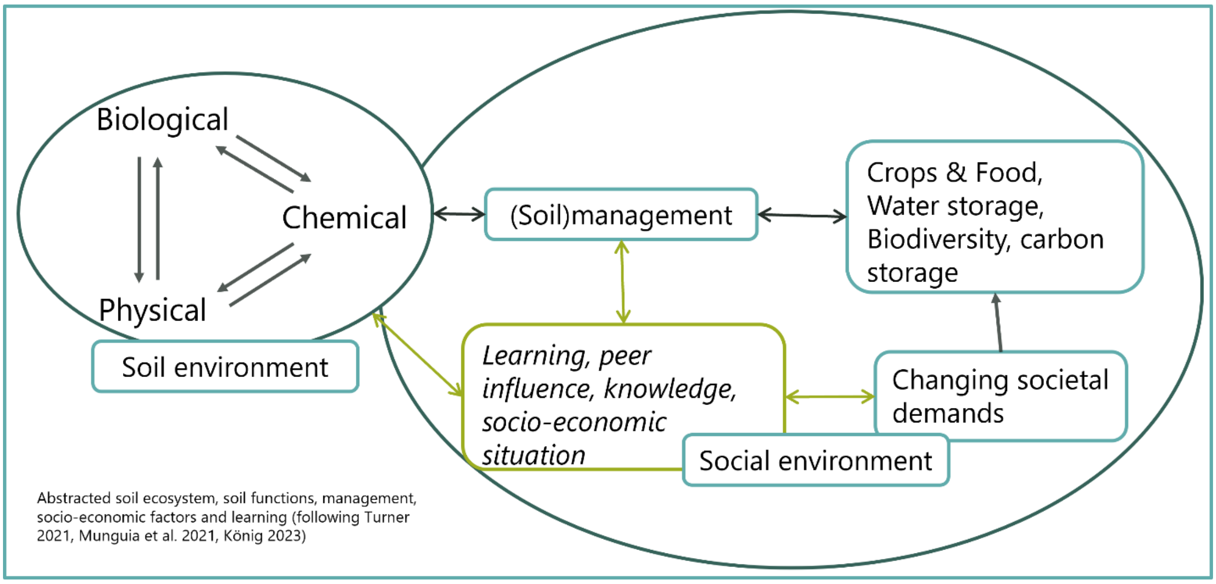

Figure 1: Conceptual model of the soil system interacting with the social system

The conceptual model consists of four interconnected subsystems: the soil environment (encompassing biological, chemical, and physical soil processes), the social environment (including learning, peer influence, and socio-economic factors), and soil management decisions that link the two environments through practice adoption choices, as well as soil ecosystem services which are influenced via changing societal demands. Unlike traditional adoption models that treat soil as a passive recipient of management inputs, this model recognizes soil as an endogenous system component that accumulates the effects of management decisions over time and feeds back into future decision-making through perceived changes in ecosystem services.

The soil environment subsystem captures the biological, chemical, and physical processes that respond to management practices and generate ecosystem services. Key processes include organic matter accumulation and nutrient cycling.

These processes operate on different timescales, creating a complex temporal dynamics of ecosystem service delivery. Soil organic matter may accumulate slowly over years or decades. The model acknowledges these differential response times while recognizing that farmers perceive them delayed as soil health improvements

The model innovation lies in connecting these soil processes to agricultural outcomes that farmers can perceive over time such as changes in water holding capacity, reduced erosion, decreased fertilizer requirements, and yield stability improvements. These outcomes become inputs to farmer decision-making processes through their influence on perceived practice attractiveness and peer learning. This aspect is modelled in the social environment subsystem incorporates established elements of technology diffusion including peer influence and knowledge acquisition However, the model recognizes that social learning about soil-dependent practices faces unique challenges because the knowledge being transmitted often concerns delayed, gradual changes rather than immediately observable outcomes.

4. Application to conservation tillage

Conservation tillage practices (including no-till, strip-till, and reduced tillage) provide an ideal illustration of the proposed model because their benefits derive primarily from soil ecosystem improvements rather than external input substitution. Ecological intensification practices (Tittonell, 2014) are promoted as one way of using the natural occurring processes in ecosystems for agricultural production, instead of an artificial suppression. Amongst these practices innovative practices is conservation tillage (no-till, strip tillage, Figure 2). Conservation tillage compared to conventional tillage (e.g. plowing on the far right) has notable benefits as it increases levels of soil organic matter, leading to higher water holding capacity, higher carbon content and nitrogen in the soil, which increase soil fertility. Furthermore, the cover of soil prevents wind and water erosion. Under conventional tillage, regular soil inversion disrupts biological activity, accelerates organic matter decomposition, and increases erosion risk. Conservation tillage eliminates or reduces these disturbances, allowing soil ecosystem processes to function more effectively over time (Paye et al. 2024).

Figure 2: Distinct types of soil tillage, the three pictures on the left are considered conservation tillage (Paye et al. 2024)

As a test case the region of Brandenburg, in eastern Germany is chosen. Several limiting factors to adoption are present in the region, cultural barriers, spatial heritage from the Agricultural Production Cooperative system in the German Democratic Republic (Klemm et al. 1998) has led to larger than usual field sizes. The agricultural area is made up of a substantial proportion of two-thirds sandy or sandy-loamy soils, which leads to low soil fertility. Low soil fertility combined with less than average rainfall (less than 600 mm/year), makes high agricultural output difficult, compared with the rest of Germany (MLUK 2024). The adoption processes of ecological intensification practices remain a research area with many unknowns and context dependencies. Prager and Posthumus (2010) assert that for farmers in Brandenburg, that next to economic factors (learning costs, implementation costs, noncompliance), and policy enforcement, "soft" factors such as reputation, satisfaction, peer pressure, personal characteristics, and the institutional regional embeddedness influence the mental model of farmers and hence their decision-making. While Prager and Posthumus (2010) highlight multiple factors with an explanatory potential for adoption, there is need to understand the mutual influencing factors and feedbacks in the system on the adoption of conservation tillage to validate causal assumptions, therefore the quantitative system dynamics method is applied (Sterman 2000).

5. Theoretical implications

The proposed model extends traditional technology adoption theory by recognizing soil as an endogneous system component rather than a passive production factor. This extension is crucial for understanding sustainable agricultural practices that derive their benefits primarily through ecosystem service enhancement.

We theorize that adoption of soil-dependent practices may follow different diffusion patterns than those predicted by traditional models. Instead of the classic S-curve driven by social contagion, soil-dependent practices may show delayed acceleration as ecosystem benefits accumulate and become observable to potential adopters (Rogers, 2003).

Comparative studies examining adoption patterns between practices with immediate benefits (e.g., improved seeds) versus those with delayed, soil-mediated benefits (e.g., conservation tillage, cover crops) could validate the core assumptions about temporal mismatch effects. Longitudinal studies tracking soil condition changes alongside farmer perceptions and adoption decisions could provide insights into the mechanisms linking ecosystem service delivery to decision-making processes.

6. Conclusion

This paper proposes understanding agricultural innovation adoption as an endogenized process involving soil ecosystem feedback within farmer decision-making processes. By treating soil as an endogenous system component that both responds to and influences management decisions, we address critical gaps in existing adoption models when applied to sustainable agricultural practices.

Conservation tillage as a sustainable practice works by enhancing soil ecosystem functions, creating delayed benefits that influence long-term adoption decisions through feedback mechanisms often ignored in traditional models. This has important implications for both theoretical understanding of agricultural innovation diffusion and practical policy design for promoting sustainable practice adoption, as time delays need to be considered in policy making. Future empirical research can be applied to design a full SD Model and refine its components, ultimately contributing to more effective strategies for accelerating the adoption of agricultural practices that may enhance both farm productivity and ecosystem health.

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