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Measuring the Supply of Ecosystem Services from Alternative Soil and Nutrient Management Practices: A Transdisciplinary, Field-Scale Approach

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Abstract: Farmers and policy makers pursue management practices that enhance water quality, increase landscape flood resiliency, and mitigate agriculture's contribution to climate change, all while remaining economically viable. This study presents a holistic assessment of how two practices influence the supply of these ecosystem services—the use of an aerator prior to manure application in haylands, and the stacked use of manure injection, cover crops, and reduced tillage in corn silage production. Field data are contextualized by semi-structured interviews that identify influences on adoption. Causal loop diagrams then illustrate feedbacks from ecosystem services onto decision making. In our study, unseen nutrient pathways are the least understood, but potentially the most important in determining the impact of a practice on ecosystem services supply. Subsurface runoff accounted for 64% to 92% of measured hydrologic phosphorus export. Average soil surface greenhouse gas flux constituted 38% to 73% of all contributions to the equivalent CO₂ footprint of practices, sometimes outweighing carbon sequestration. Farmers identified interest in better understanding unseen nutrient pathways, expressed intrinsic stewardship motivations, but highlighted financial considerations as dominating decision making. Our analysis elevates the importance of financial supports for conservation, and the need for comprehensive understandings of agroecosystem performance that include hard-to-measure pathways.

Keywords: agroecology; agriculture; decisions; tradeoffs; social-ecological systems; water quality; climate regulation; soil health; aerator; manure injection

1. Introduction

Reducing the negative environmental impacts of agriculture on the planet presents one of the most pressing sustainability challenges of the 21st century [1]. Ecosystem services provide a useful framework for understanding and analyzing the diversity of socially relevant outcomes from changing agroecosystem management toward goals of sustainability [2–4]. Ecosystem services are defined as the benefits to people provided by nature, and they represent a dynamic of supply and demand that describes the way ecosystems contribute to the well-being of human beneficiaries. Agroecosystem management influences the supply of ecosystem services by impacting underlying ecological processes [2]. Agriculture is primarily managed to maximize provisioning ecosystem services (e.g., food

and fiber production) but is dependent on, and impacts, the performance of a diversity of other ecosystem services and disservices, including clean water, climate regulation, and non-material benefits (e.g., cultural ecosystem services). Understanding the complex relationships among ecosystem services is critical to meeting growing demands for natural resources and simultaneously sustaining essential ecosystem functions and resilience [5,6].

Alternative approaches to agricultural management have the potential to increase the supply of some ecosystem services, compared to conventional agricultural production methods [7]. Extensive agroecology and conservation agriculture research suggest that best management practices (BMPs) may simultaneously enhance several ecosystem services by increasing biodiversity, soil organic matter and reducing agricultural runoff [8–10]. In particular, agroecology suggests that improving soil health should enhance multiple ecosystem services, across diverse contexts [11]. Soil health is a foundational supporting ecosystem service [12]. The term is used to describe the capacity of a soil, as a dynamic complex living resource, to support ecosystem functions and deal with stresses through a suite of interconnected physical, chemical and biological characteristics [13].

However, much of the aggregated and on-farm research points to a more complex and context-specific relationship among ecosystem service outcomes [8,14,15]. Notably, the link between water quality and soil health is tenuous, and research in the last two decades has significantly problematized prior conventions about this [15,16]. Specifically, gains in soil health can also increase subsurface nutrient flows into surface water through the development of preferential flow paths, and these outcomes may change dynamically over longer management time periods [17,18]. Additionally, while organic matter additions may increase soil carbon and the associated benefits of increases in soil health, CO₂ and N₂O fluxes from the soil surface have been shown to increase due to manure and fertilizer application practices [19,20]. Changes to soil and nutrient management strategies, both small and large, have the potential to increase, attenuate or reverse negative outcomes [2,15,20–23].

The interconnected nature of ecosystem services in agroecosystems means that both tradeoffs and synergies are possible, where changes in one ecosystem service will cause changes in another [2,6]. Assessments of tradeoffs and synergies among ecosystem services with farm management changes have primarily focused on single practices or single ecosystem services, and are often conducted using modeling to simulate environmental outcomes, though a few studies have advanced the knowledge base of bundled, on farm assessments [24,25]. In order to consider the full suite of tradeoffs and synergies, the delivery of ecosystem services from farms should be evaluated in a systems context [26].

Advancements in approaches to agroecological inquiry emphasize the integration of understanding the contextualized and complex challenges facing farmers as they seek to achieve sustainability [27,28]. Broadly, the incorporation of farmer and stakeholder perspectives can improve understandings of management and complexity in ecosystem services supply [24]. More specifically, measuring the delivery of ecosystem services through a transdisciplinary, participatory approach that integrates qualitative and quantitative knowledge could support an agroecological transition toward sustainability; such an approach has the potential to reveal both the social and ecological drivers of change, and promote on-the-ground implementation [6,29–31]. This is especially important in agricultural contexts, where farm financial viability is part of the decision-making context and ecosystem services supply may not be the dominant driver for decision making.

Widespread adoption of practices that enhance ecosystem services is only possible if those practices appeal to salient and dominant influences on decision making. Farmers' decisions are shaped by a diversity of factors at multiple scales [32]. Perceived attributes of a new management practice are some of the most important influences on adoption in the widely applied Diffusion of Innovations Theory [33]. This includes the perceived complexity, relative advantage, trialability, observability and compatibility of an innovation [34]. These attributes are considered alongside environmental and contextual factors and are socially embedded. Updated models of the Diffusion of Innovations Theory emphasize

the importance of including environmental health and environmental benefits in adoption decisions [32]. Integrating research on farmer decision making with ecosystem services outcomes from management may help identify feedbacks and connections between social and ecological elements of farm management. Further, integrating research on the social and economic dimensions of agroecosystem management with evaluations of ecosystem services provisioning can offer unique transdisciplinary insights that would not be possible from ecological or social research alone [35].

Our study addresses the call for methodological advancements and integrated research by connecting our assessment of multiple ecosystem services, from various farm management practices with a complementary, contextual social and economic analysis of decision making. Here, we measure the supply of seven ecosystem services from two dominant dairy agroecosystems in the northeastern United States to evaluate how water quality best management practices influence the performance of those ecosystem services. We selected the ecosystem services based on local and federal public policy initiatives and stakeholder input that revealed demands for ecosystem services from agricultural landscapes, including soil health, climate resilience, carbon storage, storm water storage and mitigation of agricultural runoff to surface waters [36–41].

Although policies seek to enhance joint ecosystem services in Vermont, few research projects have tried to quantify the extent to which the best management practices being used in Vermont influence ecosystem service provisioning, how tradeoffs between water quality, climate regulation and soil health are perceived by farmers, and how those perceptions influence decision making. Using a case study approach, our research fills this gap by integrating edge-of field water (EoF) monitoring, soil tests, socioeconomic analysis and greenhouse gas measurements, as transdisciplinary inquiry into ecosystem services and climate change resilience in the dominant agroecosystems of the northeastern United States. Transdisciplinary approaches value and integrate diverse knowledge systems, including indigenous, local and experiential knowledge alongside scientific or academic disciplines, and are often focused on solving problems [28]. Our study was conducted at the field scale and offers valuable insights to emerging conservation incentive ideas from policy makers who are looking to reward farmers for ecosystem provisioning at the field and farm scales.

2. Materials and Methods

2.1. Overview of Methodological Approach

Our study compares the magnitude of ecosystem services provided by alternative management systems compared to current, or conventional, management approaches in the region for two types of dairy feed production, hay and corn silage. Alternative management systems represent a distinct shift from conventional management practices for the region, and were selected based on evidence that the system had potential to increase provisioning of ecosystem services. We used public policy initiatives that reveal demand for ecosystem services from agricultural landscapes in Vermont to select the ecosystem services assessed. In 2019, Act 83, Section 3 of the Vermont legislature outlined a directive to enhance specific ecosystem services from agriculture with multiple scales of beneficiaries. These ecosystem services include soil health, climate resilience, carbon storage, storm water storage and mitigation of agricultural runoff to surface waters [36]. Together, the working landscape maintained by dairy farmers and a clean environment are essential to Vermont's character, highly valued by long-time residents and tourists, contribute to the public's sense of place and identity, are the foundations for many values and benefits and thus provide cultural ecosystem services to the public as beneficiaries [36–39].

Through collaborations with farmers, we confirmed mutually-agreeable management plans for the study sites to be adhered to for the duration of the project. Two trials of alternative soil and nutrient management strategies were initiated in partnership with Vermont farmers in 2012, and concluded in 2019. Information on social and economic dimensions of the study were also collected from our farmer partners, and other farmers in Vermont, to support transdisciplinary analysis.

In this paper, we begin by synthesizing data to assess tradeoffs in ecosystem services. First, we use data from the two on-farm trials to estimate the relative magnitude and directionality of ecosystem service provisioning at the field scale. Second, we triangulate economic data and social science research to identify drivers of management decisions for each farm trial. Third, we integrate the ecosystem services assessment with the complementary social and economic using causal loop diagrams to build a contextually specific social ecological systems concept map that highlights drivers and feedbacks into management decisions that influence ecosystem services from the dominant agroecosystems in Vermont.

2.2. Study Area—Field-Scale Paired Watersheds

To evaluate the impact of soil and nutrient management practices on ecosystem service outcomes, we implemented a field-scale paired watershed study on two dairy farms in Vermont's portion of the Lake Champlain Basin, in the northeastern US. The annual average precipitation in the study area is approximately 107 cm and the annual mean temperature is 7.2 °C. Summer (June–August) mean temperature is 17.8 °C and winter (December–February) mean temperature is −5.3 °C. Summer mean precipitation is 34 cm and winter mean precipitation is 23 cm. Paired watershed studies are used to evaluate hydrologic and water quality outcomes from land management changes by comparing a control and treatment watershed with identical, or close to identical, characteristics [42]. Our on-farm, field-scale study used adjacent fields with shared management history, landscape characteristics and soil characteristics, on two different farms, to evaluate BMPs in hay fields (*Dactylis glomerata*, *Bromus* sp., *Phalaris arundinacea*, and *Trifolium* sp.), and corn silage (*Zea mays*) production fields, representing the two dominant agroecosystems in the northeastern United States (Table 1, Figure 1). This study was conducted in situ, and management practices were implemented by farmer research partners as part of their normal farm operation. One farm evaluated the use of an aerator prior to spreading manure on a hay field. This BMP treatment was compared against a control field, where manure was spread without the aerator. The other farm evaluated a BMP treatment of combining the use of cover crops, manure injection, and reduced tillage (CCMIRT) in a corn silage production field. Reduced tillage in the BMP field was shallow strip tillage, and cereal rye (*Secale cereal*) was sown as a winter cover crop. This was compared to a control corn silage field under conventional management without cover crops, where manure was broadcast and tillage included both a chisel plow and finishing harrows. Both corn fields had intact grassed waterways which conveyed surface runoff from the field toward an edge-of-field monitoring station.

A calibration period was conducted starting October of 2012, where each pair of field-scale watersheds received the same management practices and timing of implementation. Baseline soil organic matter samples were collected in 2012. During the calibration period, both corn silage fields received broadcast manure application followed by chisel plow tillage in both fields, and cereal rye cover crop was aerially seeded into standing corn. Manure application events occurred on each field within 24 h of one another. The treatment period in the corn fields began on 9 November 2013. Both hay fields had been used for hay production for 10 years prior to this study, and both hay fields received broadcast manure application without the use of an aerator during the calibration period. The treatment period in the hay fields began on 10 June 2014. The field study period ended when the last field measurements were recorded on 3 January 2019.

Both the hay and corn fields are located in the Lake Champlain Basin within the state of Vermont (Figure 1). Importantly, Lake Champlain is considered an impaired waterway due to excessive phosphorus pollution, 41% of which is attributed to agricultural sources [43]. In June of 2016 the EPA established new phosphorus loading limits from Vermont into Lake Champlain, which was during the course of this on-farm research [37].

Table 1. Descriptions of the paired watershed fields, including management practices, soil type, aspect, area and slope.

Production Type	Field	Practices	Area (ha)	Mean Slope (%)	Aspect	Soil Type
Corn silage (<i>Zea mays</i> L.)	Conventional (<i>control</i>)	Chisel plow tillage, broadcast manure application, and grassed waterway	0.8	0.06	N	Limerick silt loam, 34.6% Winooski very fine sandy loam, 65.3%
	Best Management Practice (<i>treatment</i>)	Cover crop, manure injection, reduced till (CCMIRT), and grassed waterway	1.7	0.12	S	Limerick silt loam, 85.9% Hadley very fine sandy loam, 7% Winooski very fine sandy loam, 7%
Mixed grass-legume hay (Orchard grass, brome grass, fescue, canary grass, and clover)	Non-Aerated (<i>control</i>)	Broadcast manure application without prior aeration	2.35	3.0	S	Vergennes clay, 100%
	Aerated (<i>treatment</i>)	Aeration prior to broadcast manure application	2.75	2.7	SW	Covington silty clay, 89.4% Palatine silt loam, 1.4% Palatine silt loam, 9.4%

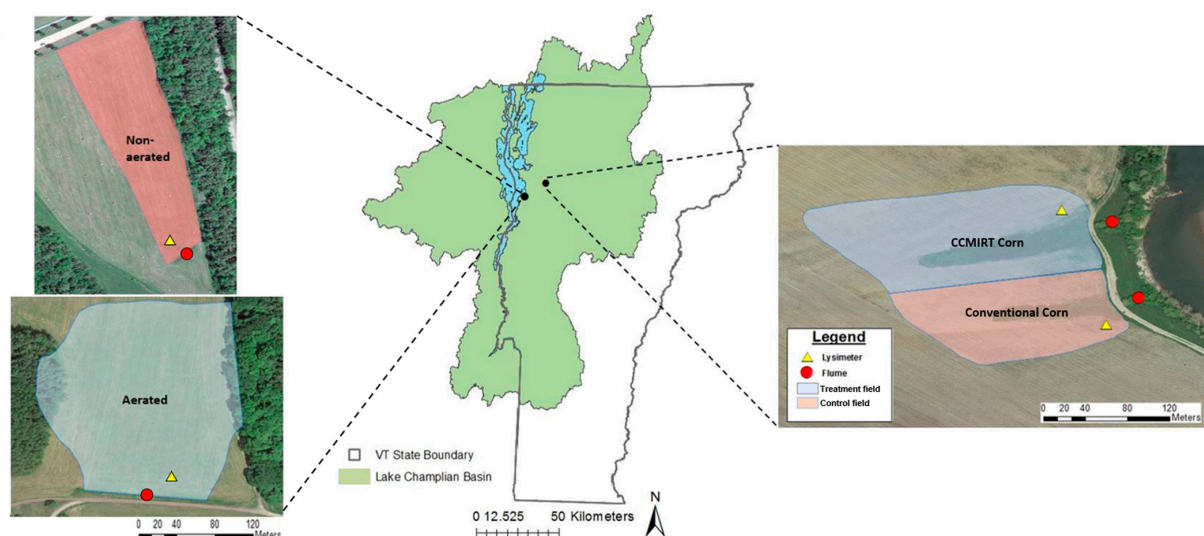


Figure 1. Location and field maps of paired watersheds within the Lake Champlain Basin. Shaded areas in field maps represent watershed boundaries (red: control field; blue: treatment field). Location of EoF monitoring station denoted by red circle and lysimeter location denoted by the yellow triangle.

2.3. Edge-of-Field Surface and Subsurface Water Quality Monitoring

Each field was equipped with an edge-of-field (EoF) monitoring station designed to catch surface runoff from the field, and a passive capillary lysimeter. Lysimeters were installed with a 63.5 cm flow divergence control tube containing a 25.4 cm diameter undisturbed soil core extending from 30.5 to 93.5 cm below the soil surface to enable collection and measurement of the quality of water that leached below the plant rooting zone (Figure 1). EoF stations for the hay fields were located at the cusp of the hay field management, and in the corn fields at the outlets of the grassed waterways. Surface runoff events were monitored from the EoF stations year-round for the duration of the study period. Water samples were analyzed for content of total phosphorus (TP), total dissolved phosphorus (TDP), total nitrogen (TN), and total dissolved nitrogen (TDN). Methods for monitoring followed those described by Twombly et al. [44]. Descriptive statistics and statistical analysis of significantly different outcomes in the EoF data attributable to the aerated hay field treatment have been published in Twombly et al. [44]. In this paper, we analyze the EoF data from the paired corn field watersheds and describe the results of this analysis alongside that conducted by Twombly et al. [44] in the results section.

2.4. Soil Health Measurements

Composite soil samples were collected to 15.25 cm depth in all fields in the second and fourth years of the trial (April 2016 and November 2018). These samples were analyzed by Cornell Soil Health Laboratory, which evaluates a suite of chemical, biological and physical indicators of soil health [45]. Evaluation included soil texture, organic matter content, soil pH, Modified Morgan Extract macro and micro nutrients, aggregate stability, active carbon, microbial respiration, available water capacity, and autoclaved citrate extractable (ACE) soil protein index [45]. Baseline soil organic matter was also measured in November 2012, before the treatment period began, using loss of weight on ignition at the Agricultural and Forestry Experiment Station Analytical Laboratory at the University of Maine [46].

2.5. Greenhouse Gas Emissions Monitoring

Greenhouse gas fluxes (carbon dioxide, CO₂, and nitrous oxide, N₂O) were measured using a portable model 1412i infrared photoacoustic spectroscopy (PAS) gas analyzer (Model 1412i, Innova Air Tech Instruments; calibrated as in Iqbal et al. [47] using static

chamber protocols [48] and established sampling techniques [47,49]. Five chambers were placed randomly in each field. Sampling occurred 2016–2018, with gas measurements taken during the growing season when soils were unfrozen (April–November) on a bi-weekly basis, with more intensive sampling around important climatic and management events (e.g., large rainfall, fertilization, or cultivation events). Gas samples were taken every minute for 10 min per chamber, and fluxes of CO₂ and N₂O were computed by fitting a linear regression of gas concentration against time after chamber closure. To estimate each field's cumulative gas flux, we integrated between each chamber's individual measurements (using trapz function in pracma package [50]) for April–November within each year. We then averaged the cumulative gas flux across the five chambers for each field.

2.6. Economic Data Collection and Analysis

Farmers' records from years 2015, 2016 and 2017 were used to develop an estimate of the costs associated with implementing each BMP. Management activity was self-reported by farmers at the end of each growing season: they provided a list of activities taken in each field (e.g., tilling, manure spreading, seeding, harvesting). The cost of each activity was measured using standard custom rates from Pennsylvania, the closest state which publishes such rates [51] to calculate costs incurred by management in each field. Published rates were similar to custom rates reported by farmers across Vermont. Farmers also reported yields and market rates which were used to estimate income attributed to each field. We used these data to estimate a yearly cost per unit area for each field, and then the cost associated with implementing each BMP, taking into account yield differences between treatments.

2.7. Yield, Forage and Manure Measurement

To estimate yield in fields, four forage subsamples were taken from each field within five days of harvest [52]. Subsamples were averaged to estimate yield per unit area, and then a composite subsample was sent to Dairy One in Ithaca, NY for analysis of dry matter (NFTA Method 2.2.1.1), and percent phosphorus (P) (CEM MARS6 microwave digestion of feed grain method). Procedures used for estimating yield and forage sampling in the hay fields are described in detail in Twombly et al. [44]. Manure application rate, manure P concentrations, harvested forage yield and forage P concentrations were measured in 2017 and 2018, and then used to calculate an annual nutrient balance based on applied and harvested P from all study fields, as described in Twombly et al. [44].

2.8. Measuring the Supply of Ecosystem Services

Our study measured indicators of seven ecosystem services, listed in Table 2. Dale and Polasky [53] outlines the criteria for selecting a set of indicators of ecosystem service performance from agriculture, emphasizing that they be both easily measured and sensitive to changes in the system. In this study, we sought to interpret our data through the most benefit-relevant indicators possible, meaning that we aimed to use metrics that capture the connection between ecological change and socially relevant outcomes [54].

Table 2. Ecosystem services measured in our case study.

Ecosystem Service	Type	Beneficiaries	Dynamic Metrics/Indicators Used
Food production	Provisioning	State and national consumers	Yield
Clean water via nutrient retention	Regulating	Champlain Basin	Phosphorus and nitrogen and exports in runoff water, including total and dissolved phosphorus loads in surface and subsurface runoff (TP and TDP), as well as dissolved and total nitrogen loads in surface runoff (TN and TDN)
Clean water via nutrient cycling		Champlain Basin	Phosphorus (P) nutrient mass balance

Table 2. Cont.

Ecosystem Service	Type	Beneficiaries	Dynamic Metrics/Indicators Used
Climate stabilization		Global	Soil organic carbon content (SOC), soil N ₂ O and CO ₂ emissions, tractor fuel consumption
Downstream flood risk reduction		Watershed	Runoff volumes
Farm resilience to extreme weather		Farm	Soil available water capacity, aggregate stability
Soil health	Supporting	Farm	Comprehensive assessment of soil health scores

2.8.1. Food Production

Food production as provisioning ecosystem services from both study sites was measured indirectly through forage yield and quality.

2.8.2. Clean Water

To assess each treatment's impact on regulating clean water, we used two complementary indicators of how each field supplied nutrient retention and nutrient cycling services, as suggested by Hammond Wagner et al. [55]. We used annual cumulative nutrient load exports as the indicators of clean water ecosystem service provisioning via nutrient retention. Manure and forage phosphorus (P) content and mass were used to calculate a nutrient mass balance for each field to indicate how the agroecosystem and field management influenced nutrient cycling. If P removed from the system in forage harvests is less than the P applied in manure, the excess would increase soil P reserves, which is prone to leaching and erosion, increasing likelihood of transport to downstream receiving waters. This imbalance would indicate an ecosystem disservice in terms of nutrient cycling.

2.8.3. Climate Stabilization

The impact of an agroecosystem on climate stabilization as an ecosystem service is indicated by assessing its overall impact on atmospheric GHG concentrations. Our study measured four different pathways impacting GHG concentrations from our field trials in equivalent metric tonnes (MT) CO₂ per hectare per year; changes in soil organic carbon stocks, N₂O emissions from the soil surface, CO₂ emissions from the soil surface, and fuel consumption.

To calculate annual changes in soil carbon stocks, we used soil organic matter content measurements from soil tests in 2012 and 2018. Using a weighted bulk density obtained from NRCS Web Soil Survey [56] for each field, and the sampling depth of 15 cm, we used the following equation to calculate annual change in metric tonnes (MT) of soil organic matter (SOM) per hectare:

$$\%SOM \times \text{bulk density } MT/m^3 \times 0.15 \text{ m} \times 10,000 \text{ m}^2 = MT \text{ SOM/ha}$$

We then calculated the carbon fraction of soil organic matter using a conversion factor of 0.5 [57]:

$$MT \text{ Carbon} = 0.5 \text{ MT SOM}$$

Then, we calculated the equivalent annual metric tonnes of CO₂ sequestered or released due to changes in SOM using molecular weights in the following equation:

$$MT \text{ CO}_2 = MT \text{ Carbon} \times \frac{44}{12}$$

We used an annual average of direct daily flux measurements to calculate N₂O and CO₂ emissions from the soil. Direct measurements were reported in mg N₂O-N/m²/hour and mg CO₂-C/m²/hour, and transformed into MT/ha/year, assuming zero emissions when the ground is frozen December through March. MT of N₂O were converted to equivalent MT CO₂ using a factor of 298.

Using farmers' records, we created a list of annual tractor tasks on each field, and then used information from Downs and Hansen [58] and Lazarus [59] to determine estimated diesel fuel use per unit area for each task. We transformed fuel volume per unit area into equivalent mass of CO₂ using the carbon dioxide emission coefficient from the US EIA [60]:

$$\text{equivalent} \frac{\text{lbs CO}_2}{\text{acre}} = 22.4 \frac{\text{gallons}}{\text{acre}}$$

After converting to metric, we generated an annual sum reported in MT CO₂ per hectare for each field. In the results section, the four different pathways of impact on equivalent MT CO₂ are reported separately for comparison in magnitude, and as total sums for each field.

2.8.4. Flood Risk Mitigation

Our study measured how management influences hydrologic response of agricultural fields and reduces storm event runoff volumes that impact peak flows and potentially downstream communities' flood risks through direct measures of surface runoff volumes in edge-of-field (EoF) stations in all fields. A reduction in surface runoff volumes indicates an increase in the supply of this ecosystem service.

2.8.5. Farm Resilience to Extreme Weather

We have limited data with which to interpret as indicators of the agroecosystem's capacity to absorb, withstand or recover from extreme precipitation shocks. We used aggregate stability as a proxy for resilience to heavy precipitation because it is a direct measure of the soils' capacity to withstand erosion from simulated rainfall. To indicate resilience to drought conditions, we use available water capacity, which is the plant available water in soil, between wilting point and field capacity.

2.8.6. Soil Health

Our study evaluated soil health using the Cornell Comprehensive Assessment of Soil Health (CASH), which includes a suite of chemical, biological, and physical measurements to give a picture of the soil's capacity to support many ecosystem functions and ecosystem services. Scores in the CASH evaluation are developed based on the observed distribution of measured values for the indicators in regional soils of similar texture [61]. Our study uses the changes in CASH scores to indicate the directionality of each field management's relative impact on overall soil health as a supporting ecosystem service over time.

2.9. Transdisciplinary Integration of Farmers' Knowledge

We engaged our farmer research partners in participatory analysis through semi-structured interviews to formalize integration of farmers' knowledge into this study. Farmers and researchers also implemented the field trial management together and shared observations during the course of the study. These interactions were referenced and recalled by farmers during the formal interviews. The semi-structured interview questions and protocol were conducted in accordance with the Declaration of Helsinki and approved by the UVM Committee on Human Subjects under project #19-0211: Exploring the Social Dimensions of Ecosystem Services in Dominant Agroecosystems of the Northeast. Interviews were consensual, confidential, and recorded.

Interviews with the two farmer-research partners lasted approximately 45 min and followed a semi-structured format so that both farmers responded to the same conversation prompts. Interviews were conducted in person. Recordings were transcribed verbatim

and then single coded using open coding to develop thematic categories, based on conventional, inductive content analysis [62]. This approach draws out direct information from participants without imposing preconceived categories or theories, to embody participants' unique perspectives. Repeated readings of the transcripts and coding notes are used to develop an organization of connected themes. In our study, primary categories of topics were developed based on successive readings of the transcripts. Repeated rounds of analysis compared codes, themes, and categories to enhance our understandings of information, meaning and relevance. This resulted in a hierarchical tree of codes which reflected emergent meanings and connected ideas, which was used to organize a description of the results.

2.10. Causal Loop Diagrams

We use causal loop diagrams to link ecosystem service provisioning to influences on adoption in a social-ecological systems model. This method depicts circles of association [63] and has been widely used to analyze and describe relationships and feedbacks in systems thinking [64]. Our analysis depicts influences and feedbacks for our two case study farms. Triangulation best addresses our pragmatic desire to bring multiple aspects and angles together for a systems level and holistic analysis of how social phenomena are situated in agroecosystem feedbacks.

3. Results

Results are presented in three sections. First, we describe the biophysical analysis through the lens of ecosystem service supply. We summarize these results in tables to communicate the implied synergies and tradeoffs, and then describe the assessment of ecosystem supply for each indicator. Second, we describe social and economic data, including economic cost–benefit analysis, and interviews with our farmer research partners. Third, we connect the biophysical and socioeconomic data using causal loop diagrams to depict relationships in the social-ecological system.

3.1. Summary of Ecosystem Services Provisioning for Each Practice

Tradeoffs in ecosystem service supply were observed in both field trials (Tables 3 and 4). Both conservation practices had negative effects on climate regulation, but positive effects on soil health. In the hay fields, aeration had no discernable impact on food provisioning or clean water regulation. However, aeration increased the overall equivalent CO₂ footprint of management, increased surface runoff volumes, and decreased soil available water capacity, but improved soil health and soil aggregate stability. In the corn fields, the CCMIRT treatment had no discernable effect on phosphorus balance, flood risk or cultural ecosystem services. CCMIRT management enhanced food provisioning, soil health, available water capacity, and soil aggregate stability, but had a negative effect on climate stabilization and clean water regulation by increasing CO₂ footprint and total nitrogen in runoff.

Table 3. Summary of supply of ecosystem services from the aerated hay field compared to the control hay field. In the last column, the symbol “≈” indicates no observable effect, “+” indicates an enhancement of ecosystem service supply attributable to the treatment, and “-” indicates reduction in the ecosystem service.

Ecosystem Service	Indicator	Key Findings	Influence on Supply
Food production	Yield	No trend in either direction was discernable based in our data.	≈
Clean water via nutrient retention	Phosphorus and nitrogen and exports in runoff water, including total and dissolved phosphorus loads in surface and subsurface runoff, as well as dissolved and total nitrogen loads in surface runoff.	The aerated hay treatment did not have a statistically significant influence on surface runoff nutrient loads compared to control hay field. Subsurface loads were large among all fields.	≈

Table 3. Cont.

Ecosystem Service	Indicator	Key Findings	Influence on Supply
Clean water via nutrient cycling	Phosphorus nutrient mass balance	No clear trend in either direction was detected. All fields had both negative and positive annual phosphorus balances during the years which were monitored.	≈
Climate stabilization	Soil carbon content, soil surface N ₂ O and CO ₂ emissions, tractor fuel consumption	Increases in soil carbon stocks offset GHG emissions from the soil surface in the treated field, and in the control. The control field was a larger equivalent CO ₂ sink than the treatment.	—
Flood risk mitigation	Surface runoff volumes	Aeration in the hay field paired trial resulted in a 16.2% increase in average event surface runoff volume when compared to the control hay field.	—
Farm resilience to extreme weather	Soil available water capacity, aggregate stability	The aerator reduced soil available water capacity, while the non-aerated field experienced increases in available water capacity. The percent of water stable aggregates increased in both hay fields, but more so in the aerated field.	—/+
Soil health	Comprehensive assessment of soil health scores	Both hay fields increased overall soil health. Using an aerator increased soil health more than not using one.	+

Table 4. Summary of supply of ecosystem services from the CCMIRT corn field compared to the control corn field. “≈” indicates no observable impact. “+” indicates an enhancement of ecosystem service supply attributable to the treatment, and “-” indicates reduction in the ecosystem service.

Ecosystem Service	Indicator	Key Findings	Influence on Supply
Food production	Yield	The CCMIRT field increasingly yielded more than the control field over time.	+
Clean water via nutrient retention	Phosphorus and nitrogen and exports in runoff water, including total and dissolved phosphorus loads in surface and subsurface runoff, as well as dissolved and total nitrogen loads in surface runoff	The CCMIRT treatment did not have a statistically significant influence on surface TDP, TP or TDN loads, but significantly increased TN loads in surface runoff compared to the control corn field.	≈/—
Clean water via nutrient cycling	Phosphorus nutrient mass balance	No clear trend in either direction was detected. All fields had both negative and positive annual phosphorus balances during the years which were monitored.	≈
Climate stabilization	Soil carbon content, soil surface N ₂ O and CO ₂ emissions, tractor fuel consumption	Increases in soil carbon stocks did not offset GHG emissions from the soil surface. The control field had a smaller equivalent CO ₂ footprint than the CCMIRT.	—

Table 4. Cont.

Ecosystem Service	Indicator	Key Findings	Influence on Supply
Flood risk mitigation	Surface runoff volume	Surface runoff volumes in the paired corn field were not significantly different by treatment.	≈
Farm resilience to extreme weather	Soil available water capacity, aggregate stability	The CCMIRT increased soil available water capacity, while the control corn field experienced decreases in available water capacity. Water stable aggregate measures declined in both corn fields, but relatively less in the CCMIRT treatment (only by 1.9% in the CCMIRT field and 7.7% in the control field).	+/+
Soil health	Comprehensive assessment of soil health scores	Both corn fields increased overall soil health. The CCMIRT field increased soil health more than the control field.	+

3.2. Soil Health

Our study observed greater increases in soil health as a supporting ecosystem service from BMP management compared to the control management. Overall CASH scores for soil health for all fields in this study increased between years 2016 and 2018, indicating that all control and treatment field management practices in our study may enhance soil health in general (Figure 2). Greater gains in scores were made in the hay fields compared to the corn fields and notably the hay field control showed no decline in any of the scores. A closer look at the individual soil tests measurements offers a more nuanced picture of changes in soil health in the Supplementary Materials.

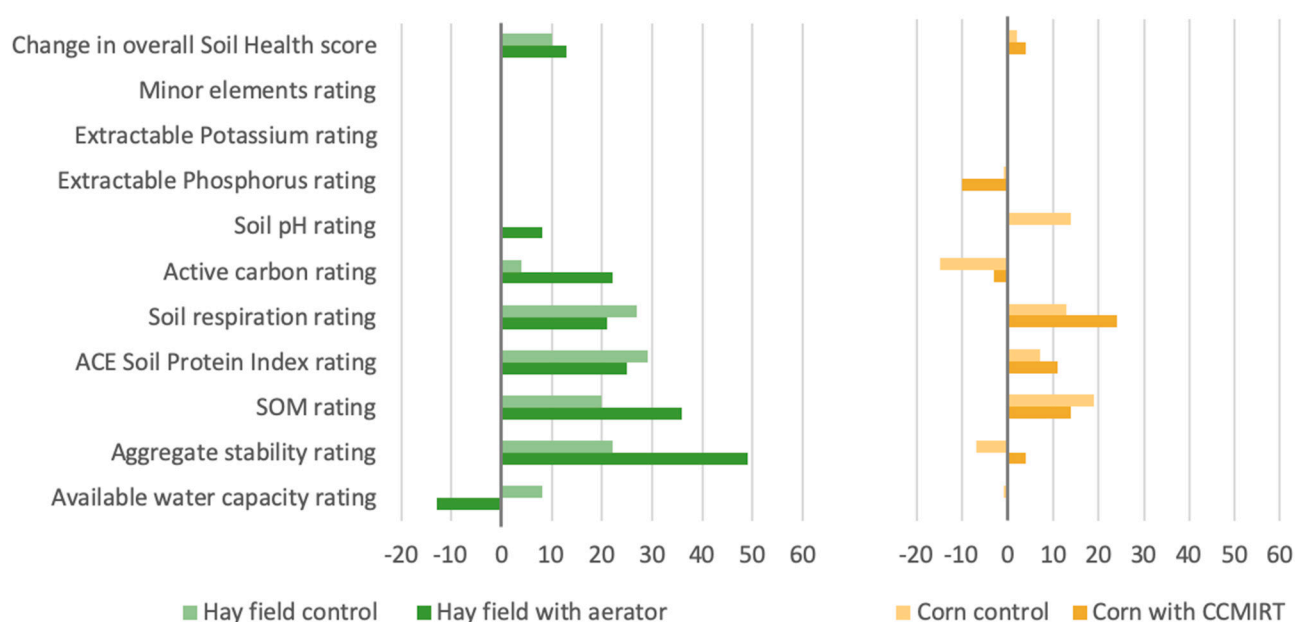


Figure 2. Changes in soil health CASH ratings and scores between 2016 to 2018 for all fields, overlaying control and treatment fields. Hay fields are depicted in shades of green on the left. Corn fields are depicted in yellow on the right.

3.3. Farm Resilience to Extreme Precipitation

Available water capacity (AWC) is a measure of the water held in the soil between permanent wilting point and field capacity. Using AWC as an indicator of field management's impact on drought resilience, fields that experienced greater soil disturbance in both agroecosystems decreased drought resilience; field management that reduced disturbance increased AWC (Figure 3). Between 2016 and 2018, AWC increased in the control hay field, and decreased in the aerated hay field. The corn CCMIRT treatment field experienced an increase in AWC. In the corn control field, we measured a reduction in AWC.

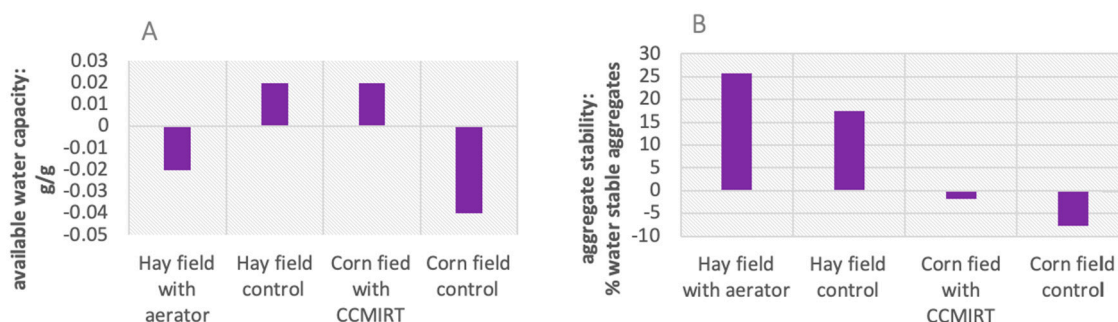


Figure 3. Change in physical indicators of soil health on all fields, 2016 to 2018. (A) There is a notable change in directionality of available water capacity between control and treatment for both BMP paired field trails, but in opposite directions. In the hay fields, the BMP reduced available water capacity, and in the corn fields, the BMP increased available water capacity. (B) Aggregate stability increased for both perennial hay fields and decreased for both annual corn fields.

We used aggregate stability as an indicator of resistance to erosion in heavy precipitation events. We observed increases in aggregate stability in both hay fields with perennial vegetation and declines in aggregate stability in both corn field treatments (Figure 3). The aerated hay field had the greatest increase in the amount of soil aggregates that withstood simulated rainfall, an increase of 26% between 2016 and 2018. In the control hay field, 17% more soil aggregates withstood the simulated rainfall test in 2018 than in 2016. Water stable aggregate measures declined in both corn fields, but only by 1.9% in the CCMIRT field and 7.7% in the control field.

3.4. Climate Stabilization

The way field management influences climate stabilization as an ecosystem service is indicated by measured changes in cumulative equivalent MT CO₂ per hectare. Changes in organic soil carbon stocks, N₂O emissions from the soil surface, CO₂ emissions from the soil surface, and fuel consumption were combined in equivalent metric tons of CO₂, as different pathways through which management influenced the agroecosystem's contribution to GHG emissions, and thus climate stabilization. Combined, N₂O and CO₂ accounted for 43% to 38% of the of the equivalent CO₂ footprint in the hay fields, and 73% to 71% of the equivalent CO₂ footprint in the corn fields. Gas flux measurements are characterized by both spatial and interannual variability. These numbers represent annual mean values based on our data. Fuel used in field management had negligible impact compared to the other pathways. N₂O and CO₂ flux measured from the soil surface account for the overwhelming majority of emissions, compared to the tractor fuel related emissions (Figure 4). N₂O flux averaged 30.99 g N₂O/ha/day in the aerated hay field, and 24.5 g N₂O/ha/day in the control hay field, which is an equivalent of 2.24 and 1.77 MT CO₂/ha/year, respectively. Measured CO₂ flux from the soil surface averaged 6.63 MT CO₂/ha/year in the aerated hay field, and 6.93 MT CO₂/ha/year in the control hay field. In the corn field trials, N₂O flux averaged 104.47 g N₂O/ha/day in the CCMIRT field, and 36.67 g N₂O/ha/day in the control field, which is an equivalent of 7.56 and 2.66 MT CO₂/ha/year, respectively. Measured CO₂ flux from the soil surface averaged 8.06 MT CO₂/ha/year in the CCMIRT

field and 6.20 MT CO₂/ha/year in the control corn field. Annual and daily averages for each year are available in the Supplementary Materials.

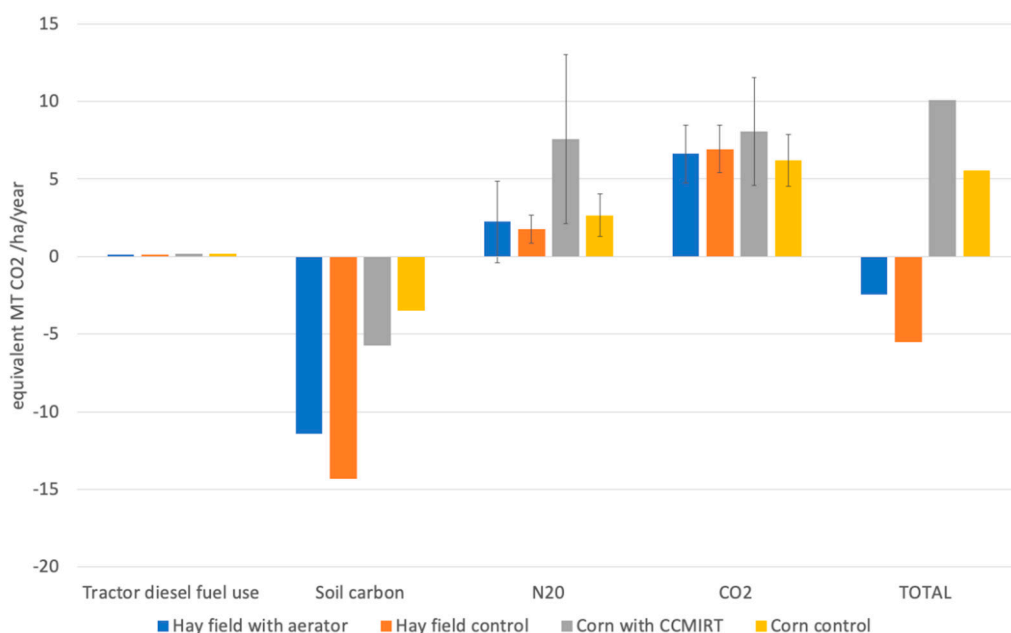


Figure 4. Equivalent metric tons of CO₂ per hectare per year by pathway measured on our case study field trials. CCMIRT is the stacked used of cover crops, manure injection and reduced tillage. Error bars are included for N₂O and CO₂ values, indicating one standard deviation above and below the mean.

Among the sources of GHG emissions measured, CO₂ flux had the greatest magnitude of impact on GHG footprint, with the exception that the N₂O flux was the largest contributor in the CCMIRT field (Figure 4). Gains in soil organic matter offset soil surface gas fluxes and fuel sourced emissions in the hay fields in our study, making them both net sinks. The control hay field performed the best in terms of climate regulation service supply, serving as an overall sink of 5.49 MT CO₂ per ha/year during the study. The CCMIRT field performed the worst, serving as a source of 10.09 MT CO₂ per ha/year. In both paired field trials, the field with less soil disturbance performed better in terms of soil carbon gains. In both trials, the control fields performed better in terms of overall contribution to climate regulation.

3.5. Clean Water

Both the control and BMP hay fields regulated clean water similarly. The CCMIRT BMP corn field reduced clean water regulation services compared to the control corn field. Average event TP and TDP loads from all fields were greater during the treatment period than during calibration period, regardless of management (see Supplementary Materials for more details). The aerated hay treatment did not have a statistically significant influence on surface runoff nutrient loads compared to the control hay field [44]. The CCMIRT treatment did not have a statistically significant influence on surface TDP, TP, or TDN loads, but significantly increased TN loads in surface runoff compared to the control corn field (*p* value of 0.1) (see Supplementary Materials for more details).

The subsurface nutrient export measured in our study was sizeable (Table 5, Figure 5), but not statistically attributable to field management because each field had a single lysimeter, which was installed after the calibration period. Large uncertainty exists in the accuracy of extrapolated leaching data (volumes and nutrient loads) as a result of only having a single subsurface measurement point within each field. For example, over 1100 mm of leachate was measured in aerated hay in 2017, indicating that macropore intersection with the lysimeter was likely, leading to significant preferential flow. In the

corn fields, subsurface TP load was 91% of the total measured TP load exported from both pathways in 2017 and 2018, and 92% of total TDP export. In the hay fields, subsurface TP load was 64% of the total measured TP load exported from both pathways in 2017 and 2018, and 66% of total TDP export.

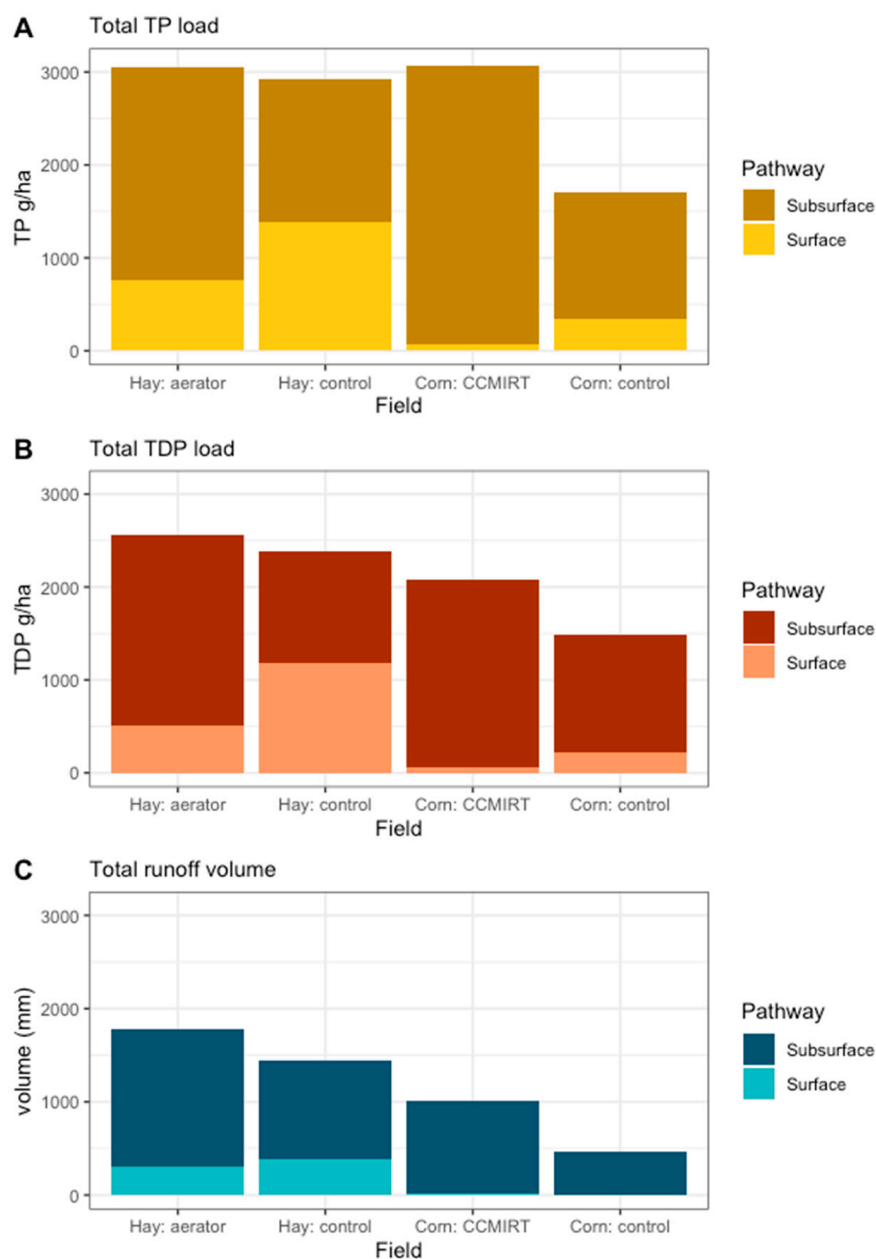


Figure 5. (A) Total phosphorus exports via surface and subsurface pathways, cumulative over years 2017 and 2018 for all four fields. (B) Total dissolved phosphorus exports via surface and subsurface pathways, cumulative over years 2017 and 2018 for all four fields. (C) Total hydrologic exports via surface and subsurface pathways, cumulative over years 2017 and 2018 for all four fields. Hay fields are on fine textured, clay soils. Corn fields are on coarse textured soil.

Field-scale P balances indicate how the field management contributes to excess P reserves, which contribute to the long-term water quality degradation in the phosphorus impaired watershed. The P balance in each field (Table 6) shows annual variability in the amount of P applied and P harvested within each agroecosystem our study monitored. These field-scale P balances do not indicate a trend in directionality of ecosystem service

supply from any of the fields. Over the years for which these data were collected and analyzed, each field had both a negative and positive P balance, with no clear trends in either direction. However, the magnitude of P cycling through the system is notably far greater in the corn agroecosystem, compared to the hay agroecosystem. Manure applied P in the hay fields was only 27% of the P applied in the corn fields. Harvested P in the hay fields was only 22% that harvested from the corn fields.

Table 5. Summary of annual hydrologic and P exports via surface runoff and subsurface leaching. Volume (as a depth) and P load values are expressed as annual sums. Hay field data have been published in Twombly et al. [44].

Field	Year	Volume (mm)		TP (g/ha)		TDP (g/ha)	
		Runoff	Leachate	Runoff	Leachate	Runoff	Leachate
Control corn field	2017	4.21	108	166	167	52.1	130
	2018	3.83	347	180	1190	163	1140
CCMIRT corn field	2017	5.72	252	38.0	531	27.4	456
	2018	5.00	743	36.5	2470	30.8	1560
Control hay field	2017	242.1	724.1	688.56	1096.5	537.97	775.2
	2018	146.3	333.5	701.57	439.8	648.38	416.3
Aerated hay field	2017	182.1	1109.1	381.16	1909.4	219.17	1744.3
	2018	124.8	371.7	378.62	384.7	289.82	313.4

Table 6. Field phosphorus balance, based on P applied in manure and P removed in harvest.

Year by Field	Manure P Applied (kg/ha)	Forage P Harvested (kg/ha)	Balance
<u>Hay field with aerator</u>			
2016	20.8	15.9	4.9
2017	10.2	20.7	−10.5
2018	14.7	12	2.7
<u>Control hay field</u>			
2016	22.2	16.1	6.1
2017	11.1	18.9	−7.8
2018	15.1	13.1	2
<u>CCMIRT corn Field</u>			
2017	98.4	73.5	2.7
2018	13.9	57.9	−33.9
<u>Control corn field</u>			
2017	89.8	87.1	24.9
2018	23.5	57.4	−44

3.6. Flood Risk Mitigation

Surface runoff volumes were used to indicate how management influenced downstream flood risk mitigation. Runoff volumes were greater in the hay fields, compared to the corn fields, likely due to soil texture differences (Table 5). Aeration in the hay field paired trial resulted in a 16.2% increase in average event surface runoff volume when compared to the control hay field [44]. Surface runoff volumes in the paired corn fields were not significantly different by treatment. The average difference between the surface runoff volume generated by the CCMIRT field and the control corn field was 19.2 m³/ha during the calibration period, and 23.0 m³/ha during the treatment period. Using a Mann–Whitney U test, the difference in volume during the treatment period was not significantly different from the calibration period (*p* value of 0.89).

Aggregate stability increased in both hay fields and decreased in both corn fields during the trial period (Figure 3). The greatest increase in aggregate stability was observed

in the aerated hay field, the same field which resulted in an increase in surface runoff volume. This suggests that dynamic changes in soil structure due to management and soil biology, which are known to enhance water infiltration, are not a dominating driver of field-scale hydrologic response. This confirms other research literature, that aggregate stability and soil biology alone are inadequate predictors of the performance of this ecosystem service. Runoff volumes at the field scale are influenced by other landscape features, such as soil texture, antecedent moisture condition, and surface cover.

3.7. Food Provisioning

Our study observed greater increases in yield in the CCMIRT treatment than the corn control treatment, but no discernable trend in either direction for the aerated hay field treatment compared to the control. Similarly, we found no discernable difference in yields between the aerated versus control hay field treatments. In 2016, the CCMIRT corn field and control corn field had the same average yield, but over the next two years, the CCMIRT treatment increasingly yielded more than the control field (Figure 6). In the final year of the study, the CCMIRT corn field yielded 11% (5.6 MT/ha) more than the control field (Figure 6).

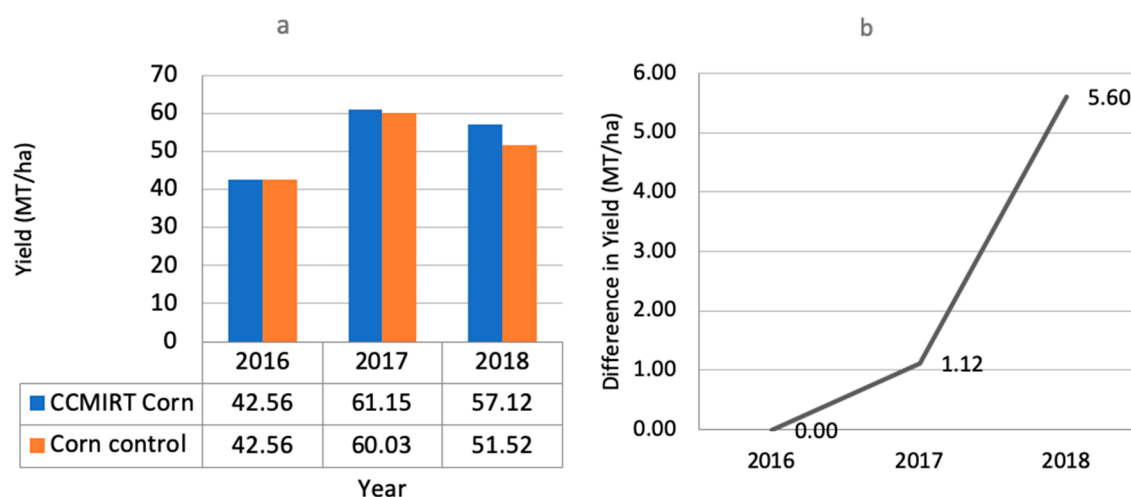


Figure 6. (a) Annual yields in the control corn field and the cover crop, manure injection, reduced till (CCMIRT) corn field. (b) The difference in yield between fields in years 2016, 2017 and 2018. The difference in yield between fields in the corn trial increased over time.

3.8. Economic Cost–Benefit Analysis

Using farmers' records and custom rates, our analysis determined that the extra cost of equipment associated with best management practices was greater than gains in income from increased yields, for both paired field trials during years 2015 through 2017. This was true in both systems (hay and corn) and for all years of the study. A detailed account of our analysis is included in the Supplementary Materials.

Revenues were similar for both corn fields in the years 2015–2017. Estimated costs of management were higher for the manure injection treatment, resulting in a smaller gross margin per unit area for the CCMIRT treatment field (see Supplementary Materials for details). The average gross margin per hectare was \$2157.43 for the control corn field and \$1735.05 for the CCMIRT managed field. Overall, our cost–benefit analysis determined that the CCMIRT treatment grossed \$422.38 per hectare less than the control corn field.

The added cost of using the aerator in the treatment hay field was \$71.66 per hectare in 2015 and \$42.01 per hectare in 2016 and 2017. Variability in yields and the cost of baling hay drove a fluctuating annual gross margin for both hay fields (see Supplementary Materials for details). The average gross margin per hectare was \$41.05 for the control hay field

and \$5.14 for the aerated hay field. Overall, our cost–benefit analysis determined that the aeration treatment grossed \$35.91 per hectare less than the control corn field.

3.9. Farmers' Perspectives

Thematic analysis of the interviews with farmers identified in situ perceived advantages and drawbacks of the management practices being trialed, the most important considerations that dominate farm management decisions, observations made during the paired watershed field trials, and their reflections on the research.

3.9.1. Influences on Decision Making

Our farmer research partners identified many advantages associated with the best management practices they trialed as part of this study. Primary drawbacks discussed were perceived logistical challenges, such as accessing and transporting equipment, and carving out time during busy season. They also discussed how changes made on their farms over decades and through multiple generations had been proactive about environmental stewardship at times and overwhelmingly influenced or constrained by the economic climate, the price of milk and the farm's capacity to stay in business. Farm financial viability emerged as the primary filter through which all other management considerations were run and was described as the primary decision-making determinant. However, many other agronomic, environmental, social, and quality of life considerations influence planning and decision making. Conservation incentive programs were named as the primary reason each farmer had originally adopted the new practices.

3.9.2. Farm Considerations

Interviews revealed the importance of practical farm management considerations among the most salient perceived advantages and drawbacks of the trialed practices. Farmers discussed how logistical challenges and time demands influenced the degree to which they perceived the practice as being compatible with their farming operations, and how it impacted their quality of life. This was often described in terms of time saved, or logistical and scheduling challenges. Farmers also valued practices for the way they might increase nutrient availability to plants and enhance forage health and yield. Finally, farmers described the potential for each practice to enhance their relationships with neighbors. In the case of manure injection, this was due to reduced odors associated with manure application, whereas the aerator was described as supporting the farmer's reputation as being proactive about water quality concerns.

3.9.3. Stewardship and Landscape Multifunctionality

Farmers pursue management decisions that balance environmental stewardship with farm viability. Both farmers described examples of the way environmental stewardship had shaped their decisions in the past when they had the financial capacity, such as proactively installing buffers, reducing feed-based P imports, or moving cows farther away from waterways. However, both farmers pointed out that environmental stewardship may not drive farm decisions alone—management changes need to have co-benefits that align with farm goals. As one farmer described, *"farmers will adopt practices that save them or make them money. They're not going to ... [adopt a practice] ... just because it's going to protect water quality, that's just the reality."* Farmers further described the way nutrient cycling and water quality outcomes were connected by environmental and agronomic benefits; *"protecting water quality should be where good environmentalism and good economics come together because if all your nutrients are running off your farm and running into the lake, you're throwing money away. Those are nutrients you want to capture and recycle."* This rationale of coupled economic and environmental benefits was described as sensitive to the economic climate. Farmers differentiated between the economically constrained situation they find themselves in currently, and the way they invested freely in conservation when they had greater financial flexibility and profitability. As one farmer described, *"when times were*

good a few years ago and some of those big partners were making like crazy amounts of money, they were improving their farms. They were putting in grass waterways and, upgrading their manure systems and they were doing things that would both benefit them economically and would be good environmental practices”.

3.9.4. External Pressures: Financial Climate and Drought

External pressures both constrain and enable farmers to invest in conservation practices. Farmers observed that most of their current decisions were made with an understanding of how it would influence farm efficiency, by thinking in terms of milk per acre, and reduced costs for the farm. Cost-share incentive programs were mentioned as the primary reason farmers had originally adopted the trialed practices. Likewise, the milk price crisis that coincided with our interviews revealed the extent to which off-farm financial market pressures have constrained farmers’ decisions. As the farmer who conducted the CCMIRT trial observed; *“with the way the economics has been in dairy farming, we’re very aware of anything that we do or spend money on that doesn’t have a direct result of cows making more milk. Maintaining the grass waterway or a buffer around a field . . . It doesn’t make us any money whatsoever... We do it because it’s the right thing to do.”* The grass-based farmer described how financial considerations limited the extent to which they could transition to a grass-based feed; *“I know from a greenhouse gas consideration we shouldn’t be feeding grain to our cows, so we should be an all-grass dairy. But the economic impact of that would be significant. We just can’t afford to”.*

3.9.5. Adaptive Management

Both farmers described the way their management of the research fields was refined over time and how they were constantly thinking about improvements to management that would increase positive outcomes. Adopting new practices was described as the beginning of a learning process, that would be refined over years to hone in on how it could be best integrated with their farming systems and environmental conditions. Science-based information, including that collected during the study, informs management alongside farmers’ observations. One farmer said, *“The more information we get, the better it’s going to be, and the more useful it’s going to be.”* Implementation of practices was described as changing and evolving over years; *“any practice that you’re trying to implement, it’s gonna take us years to . . . figure out when to use it, and what’s the best conditions, and where it’s most beneficial”.*

3.9.6. Invisible Pathways

Reflecting on their interest in the information collected by our research team, farmers identified the “unseen” pathways and outcomes in the agroecosystem dynamics as the most interesting pieces of the research results. For one farmer, it was the gas fluxes and for the other farmer, it was the water borne nutrient exports and how related nutrient retention could enhance yields. One farmer research partner remarked on how invisible outcomes and pathways have less of an influence on their decision making than those that are visible; *“you don’t see gasses leaving the field, even though scientists tell you that it is happening. That’s a little harder to sell”.*

3.9.7. Participatory Analysis

Farmers made observations about their agroecosystem that align with the data collected, provided valued insight into the outcomes of each practice, and contributed to our collective analysis of the study. The farmer who conducted the CCMIRT corn trial described how well the grassed waterways worked from his perspective. He suggested, *“that may be the takeaway—that having your grass waterways the right width for the area the water’s collecting from, that may be the key right there. I mean, if they’re wide enough, you don’t get any water actually running off the field.”* This aligns with our collected data. In fact, the corn fields generated so few paired runoff events, that it limited the comparative analysis we could conduct. The farmer who trialed the aerator on hay fields noticed that the grasses

in the aerated field seemed more stressed during times of drought. He suggested it was detrimental in dry conditions, noting that, “it was like it dried out and nothing grew back. And I think by opening the soil up . . . it dried it out more. Whereas the field that we didn’t aerate, it seemed . . . the sod held more of the moisture in place. . . . I think we just need to learn more about how- how and when to use it.” This observation aligns with our soil data on reduced available water capacity in the aerated field.

3.10. Causal Loop Diagrams

We used causal loop diagramming to integrate the measured outcomes and the qualitative social data presented above. Our causal loop diagram illustrates feedbacks on decision making in these two agroecosystems and highlights how ecosystem services can be feedbacks on management. Measured outcomes (Tables 3 and 4) were used to populate the ecological aspects of the diagram and determine positive or negative influences. Thematic analysis of influences in decision making was used to populate the social aspects and feedbacks depicted in the diagram. Re-reading of the interview transcripts supported this process in determining relationships among factors and the influences on decision making which were most salient that link to ecosystem service outcomes.

Both diagrams indicate that there are some ecosystem services which are important to farm management decisions and some which were not identified as highly salient on these farms. The diagram highlights soil health as an important intermediary that supports multiple outcomes which feed back to management (Figures 7 and 8). For both farms, farm financial viability in the face of the dominant economic climate was named as the primary filter through which management decisions were made and the causal loop diagram was modified to reflect this.

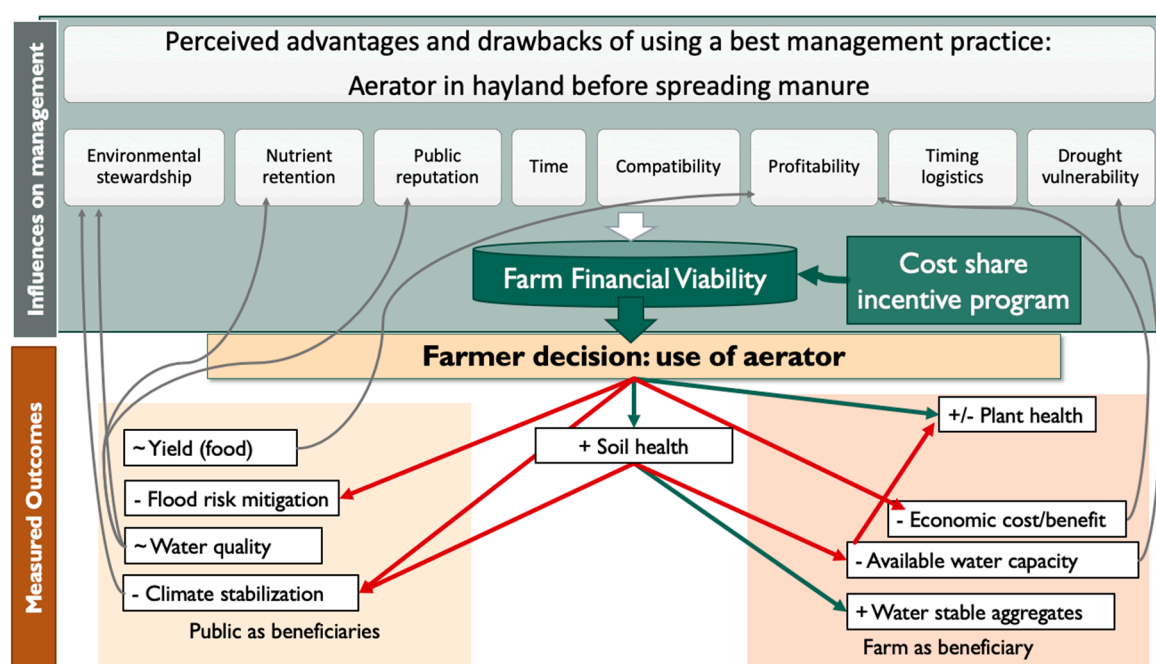


Figure 7. Feedbacks from outcomes to influences on management decision to use the aerator, based on farmer interview data coupled with measured outcomes from our field trial. Feedbacks are identified in grey arrows. Beneficial outcomes are indicated by green arrows and ‘+’ symbol. Negative outcomes are indicated by red arrows and ‘−’ symbol. Farm financial viability in the face of the dominant economic climate was named as the primary filter through which management decisions were made.

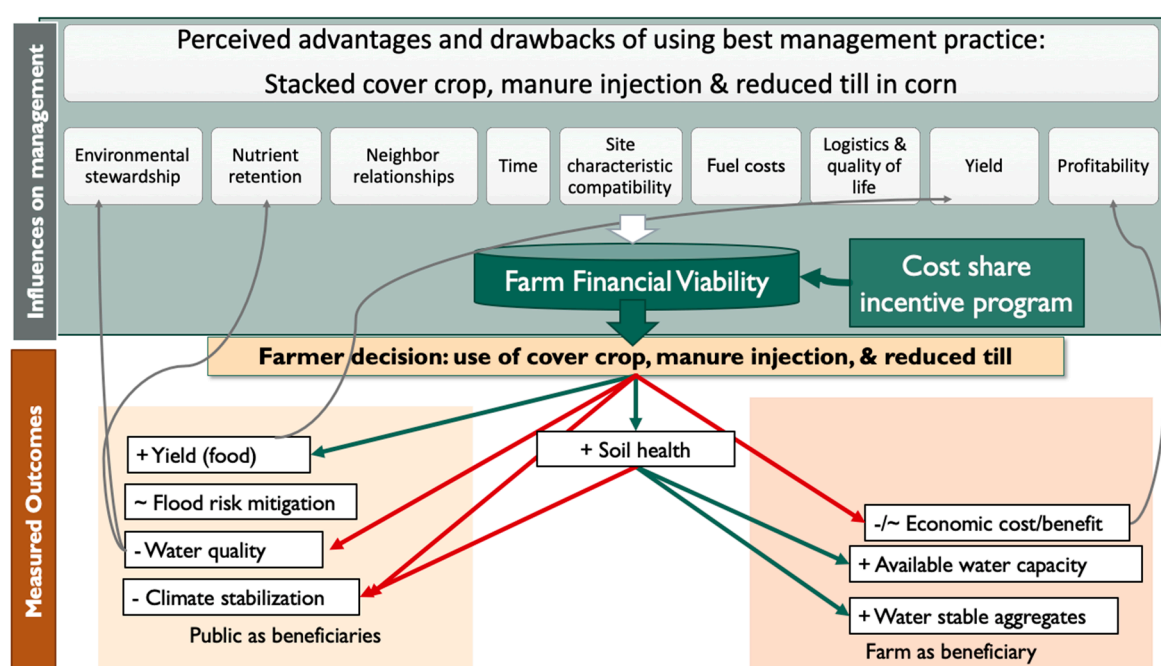


Figure 8. Feedbacks from outcomes to influences on the decision to use the CCMIRT, based on farmer interview data coupled with measured outcomes from our field trial. Feedbacks are identified in grey arrows. Beneficial outcomes are indicated by green arrows and '+' symbol. Negative outcomes are indicated by red arrows and '-' symbol. Farm financial viability in the face of dominant economic climate was named as the primary filter through which management decisions were made.

In the aerator trial, yield, drought resilience, water quality, GHG emissions, and economic cost–benefit analysis were named as outcomes measured by our study which were of interest to the farmer's management decisions (Figure 7). Our monitoring found no significant impact on water quality outcomes, but did find that the practice enhanced soil carbon sequestration, which feeds back into environmental stewardship as a motivating factor. Perceived water quality benefits are linked to enhancing the public reputation of the farm, even though our study found no significant water quality benefits. Increased vulnerability to drought conditions noticed by the farmers aligns with the measured indicator of reduced available water capacity in the aerated field. The study found no discernable impact on yields due to the aerator, but this was noted as an outcome that would have important implications for management if there had been a measurable impact. Flood risk mitigation resilience to extreme precipitation was not mentioned. Finally, the farmer indicated that the economic cost–benefit analysis would be one of the most important feedbacks on whether or not they continue to use the practice. Our study indicated a slightly higher cost per unit area associated with the aerator.

In the CCMIRT trial, we documented both positive and negative feedbacks on management (Figure 8). During the interview, the farmer described an interest in water quality outcomes that reflected both an environmental stewardship ethic and a desire to retain nutrients within the agroecosystem. Our study found a statistically significant increase in nitrogen losses in surface runoff in the CCMIRT treatment, which will be a negative feedback, considered alongside other factors in decision making. Comparative increases in yields in the CCMIRT treatment were observed in our trial, which was identified as having a positive impact on decision making. Finally, our economic cost–benefit showed that both fields had positive gross margins, but that the control corn field had a greater gross margin, which may be a negative feedback on the decision to use CCMIRT.

4. Discussion

4.1. Main Findings

Our study found that both of the alternative soil and nutrient management practices we trialed (using an aerator in haylands, and the stacked use of cover crops, manure injection and reduced tillage in corn silage production) had negative and positive outcomes for ecosystem services. This presents challenging tradeoffs for both farmer adoption and policy implementation. Through combining multiple indicators, we identified unseen pathways as potentially the most important in determining the overall impact of a practice on ecosystem services supply. Specifically, subsurface phosphorus leaching accounted for 64% to 92% of hydrologic phosphorus export from fields. Greenhouse gas flux from the soil surface constituted 38% to 73% of all contributions to the equivalent CO₂ footprint of the practices we evaluated. Our study draws these estimates from the available data collected on four fields, but measurement of these unseen pathways is challenging, characterized by uncertainty, and presents a critical need for future research. Annual mean soil surface emissions outweighed gains in soil carbon in both corn fields, making them net sources greenhouse gasses, while both hay fields were net sinks. Our findings concur with assessments of agroecological farming systems by Boerave et al. [25] that the inclusion of multiple indicators offers a more nuanced and accurate quantification of ecosystem service supply. These results further demonstrate that many practices have environmental, social and economic tradeoffs. Silver bullets in agricultural management to achieve all optimal outcomes are rare.

As policy makers seek to enhance ecosystem services from agriculture, payment for ecosystem programs with adequate payment levels will be critical to supporting the adoption of recommended practices for many farms. Although not mentioned by farmers in our interviews, regulations can help drive management changes on farms by requiring them. Our analysis suggests that regulatory approaches be considered carefully in light the technical and financial resources farmers need in order to comply. Our cost–benefit analysis showed that alternative practices provided a reduced gross margin to farmers, despite some yield increases. Our results suggest that nutrient flow aspects of agroecosystem performance are of interest to farmers, and play into management changes, but cultivating positive ecosystem services do not dominate decision making. The way management effects farm financial viability against the backdrop of fluctuating commodity market pressures was described as the primary filter used for making farm management decisions in our study. However, information about complex and unseen nutrient dynamics is of interest to farmers and policy makers, and thus presents an important opportunity for research and education.

4.2. Biophysical Outcomes

Tradeoffs in ecosystem services were identified in both management trials in this study. Enhanced performance of ecosystem services primarily accrued to services where the farm was the primary beneficiary, and reductions in performance was observed in ecosystem services to which the public would be the beneficiary. This finding is consistent with Schipanski et al. [24] who found tradeoffs between ecosystem services and economic metrics. Both of the BMPs we evaluated enhanced soil health scores, despite offering tradeoffs among other ecosystem services. This is an important finding for conservation professionals in the agricultural community, and is especially important for policy makers who make decisions based on a heuristic that assumes improved soil health translates into enhancements in ecosystem services [36]. Our research indicates this is not always the case. It further suggests that soil health as a principle of agroecology should be carefully re-examined, as it can present contextually specific environmental or social tradeoffs.

Our assessment of ecosystem services supply from using an aerator showed primarily negligible or negative impacts. Importantly, surface water quality was statistically unaffected by using the aerator, though farmers value it for its purported water quality benefits. We measured reductions in performance of climate regulation and flood risk reduction

services in the aerated hay field. Observed increases in surface runoff volume was likely due to the fine textured soil in the site, which is prone to soil surface sealing caused by the aerator implement [44]. Soil carbon gains in the top 15 cm of the soil profile, which are known to often be high in clay soils [65], were substantial in both hay fields, suggesting that hay fields can supply important climate regulation services regardless whether or not an aerator is used. While some important ecosystem services were reduced by the aerator, the practice enhanced soil health and had no discrete effect on yields. While increases in aggregate stability in the aerated field indicated enhanced resilience to heavy precipitation, we also found that the practice reduced resilience to drought (available water capacity).

The CCMIRT practice enhanced ecosystem services that the farm is the primary beneficiary of, and decreased key environmental ecosystem services that benefit the public. Specifically, CCMIRT enhanced soil health, food provisioning and farm resilience to extreme weather, but reduced climate regulation and clean water regulation services. However, this outcome is likely very context dependent, as the supply of water quality regulating ecosystem services may be more influenced by landscape and soil texture characteristics than soil management practices [66]. Importantly, our study suggests that appropriately sized grassed waterways at the edge of field can be so effective in reducing nutrient rich surface runoff, that they dominate the impact of soil and nutrient management strategies like CCMIRT. The tradeoff in climate regulation services aligns with other research in our bioregion finding that manure injection increases N₂O emissions by subjecting manure to anaerobic conditions in the soil, as opposed to surface application [20,49]. Our study reinforces the importance of better understanding soil greenhouse gas emissions and their drivers, as well as the importance of including them in ecosystem service assessments.

The limited effectiveness of recommended practices in enhancing clean water regulation is not anomalous. Other studies on the water quality performance of best management practices report mixed effectiveness, from negative impacts to complete elimination of runoff [21]. However, while more detailed research on the mechanisms responsible for nutrient transport and flux in these agroecosystems is needed, our transdisciplinary findings suggest that landscape features, or structural BMPs such as grassed waterways, may be some of the most important determinants of water quality outcomes from these fields. Grassed waterways proved to be very effective, perhaps dominating the nature of surface runoff volume and nutrient export from the corn fields.

Soil carbon gains observed in our study range from 0.95 to 3.9 MT C/ha, which is within reported ranges from other studies, but also suggests that there may be room for better performance in this metric. Soil organic matter gains have been linked to the use of cover crops, additions of organic fertilizers (such as manure), and conservation tillage [67], yet few studies evaluate the impacts of stacking these practices together. [68] found annual sequestration rates of up to 10 MT C/ha/year in fields with organic amendments. One recent study found that winter cover crops increase active carbon, in annual vegetable production systems, but that compost additions were responsible for the majority of soil organic matter increases [69]. They measured increases of 9.6 Mg C/ha due to compost additions and 3.4 Mg C/ha due to cover crops, attributing labile carbon gains to the cover crops. Similarly, our study attributes soil organic matter gains to manure additions. This aligns with other research, including meta-analysis by Gattinger et al., [70] who found that annual carbon inputs from organic fertilizers influence the organic matter and carbon sequestration gains observed in agricultural soils. Additionally, surface applied dairy liquid manure in no-till cropping systems has been observed to increase soil carbon stocks and aggregation [71].

4.3. Social and Economic Elements

Social, environmental, quality of life, and economic factors influenced farmers' decision making about management in our study, and in turn, the supply of ecosystem services from their landscapes. These factors were revealed to be both individual and structural, and while a case study cannot be representative of the entire community of farmers, our

work reveals several insights. Both farmers in our case study identified dominant economic pressures as driving their farm planning, financial cost-share programs as the primary reason they decided to try a new practice, and that they also consider the environmental footprint of the farm when making decisions. Environmental stewardship, quality of life, cost-share incentives, equipment, and financial barriers have been identified in other research on factors influencing the adoption of new practices [72,73], but the dominance of financial concerns in our study is an important finding. It reflects the impact of the concurrent dairy farm financial crisis at the time of our study, when the milk market was paying farmers below the cost of production and 13% of dairy farms in the state of Vermont went out of business [74].

Our study finds that invisible or less understood processes and pathways can have a dominating effect on ecosystem services supply outcomes, but are less factored into decision making. This is consistent with other scholarship on how psychological proximity influences the likelihood of action [75]. While this aspect is consistent with other research, it suggests more information about invisible processes and environmental outcomes may enhance environmental decision making if farmers have the financial capacity to do so.

The salient perceived benefits and drawbacks of the practices in our study better align with the updated model of farmer decision making developed by White and Selfa [32] than in the popular Diffusion of Innovations Theory [33]. White and Selfa [32] add emphasis on environmental conservation and perceptions of healthy environment. This includes environmental benefits among important considerations of relative advantage, profitability, and efficiency. We recommend that future research and outreach should seek to make visible the invisible pathways and the greatest leverage points for change in ecosystem service delivery.

4.4. Integrative Elements

In this case study, we offer a picture of the social and ecological dimensions that must be understood together to pursue agricultural sustainability in any context around the world, that is the ecological outcomes of changes in farm management, and the social factors that influence those changes. These social and ecological elements are contextually nuanced, in the location of our study, and in every region of the world. While by the nature of a case study, we cannot infer broadly from our findings, they are incredibly relevant to the local context in which we have conducted our study. We have provided the contextually relevant information needed to support decision making by local farmers and policy makers. This is work that is needed everywhere—to highlight social and economic factors that influence adoption of recommended management practices, account for the ecosystem services they provide, and illustrate the opportunities for intervention that will support a more sustainable future. Our approach to documenting the socially relevant ecological outcomes from sustainable agriculture practices, and the social factors that influence the adoption of practices could be replicated in any location or context.

Integrating social, economic and biophysical elements of our study through causal loop diagramming was effective for illustrating feedbacks from measured outcomes into decision making, and placing them in a realistic context. Ecosystem services that deliver benefits to both the public and farm were identified as feedbacks on farmer decision making. This method also allowed us to depict important mediating factors on both social and ecological sides of our study. Farm financial viability and payment for ecosystem services programs like conservation practice cost-share incentive programs were identified as a primary, but not sole, influence on farm management. Farmers were also motivated by an environmental stewardship ethic and understandings of nutrient cycling. Soil health was identified as playing an important mediating role in supporting the performance of some of the ecosystem services we measured, but not all of them. Interventions that reinforce stewardship motivations and enhance understandings of how soil health interacts with nutrient dynamics emerge as important leverage points for supporting the pursuit of agricultural sustainability in this community.

4.5. Limitations

Our study provides a window into tradeoffs, synergies and feedbacks in ecosystem services from agricultural management in the field, but is a case study with limited data. Our results cannot be extrapolated to all fields managed in the same way due to influences of soil texture, climate and landscape position on environmental outcomes, as well as the limited and variable data we had available on unseen pathways in our study. However, our study does suggest that what was observed on these two farms could happen elsewhere, and more robust and comparable data are needed. Likewise, our social and economic data were only collected from the two farms.

We find the limitations in our data as a worthwhile record for future researchers who wish to take a similar approach. While the water quality and soil organic matter data were compared in a rigorous and comparable way with baseline data, some of the data are limited because data collection began after treatment was started. Thus, we could not compare those measurements to the state of the system before management changes occurred, and our assessment is based on how changes over time differed between paired fields. This is common, but limits the strength of analysis [76]. In our study, this includes most of the soil health testing, soil surface GHG fluxes, subsurface water quality via lysimeters, and yields. Future research should seek to measure all parameters prior to treatment, to offer a baseline comparison, as well as monitor how changes over time differ by treatment.

Our methods allow us to attribute statistically significant differences in surface pathways of hydrologic nutrient export, but our limited subsurface pathway data do not allow us to make statistical inference on differences in subsurface P export between treatment and control fields. Additional lysimeters installed within each field would have reduced the large uncertainty associated with using a single measurement point to estimate leaching volumes and nutrient loads. However, the subsurface water quality data we collected indicate that subsurface hydrologic pathways could be a significant portion of the total phosphorus loss from these fields, and indicate a clear need for future research.

Our soil samples were collected as composite samples to a depth of 15 cm. This method aggregates soil cores from across the field, mixes them, and then conducts testing on the aggregate/composite sample. Using composite samples accounts for spatial variability and is standard practice. However, SOC is characterized by a high degree of spatial variability [77,78] and could be responsible for some of the observed changes in our sampling. Our soil sampling is also limited by the depth of measurement. Most changes in soil carbon occur near the soil surface, but IPCC guidelines for GHG inventories [79] recommends sampling to a depth of 30 cm, and other studies suggest that samples from even deeper are necessary to account for all changes [80]. Future studies should sample to 30 cm depth or farther. Excluding soil carbon in the 15–30 cm range may have caused us to underestimate our assessment of climate stabilization services. Carbon sequestration studies that measure bulk density, rather than estimating based on soil survey data, are significantly higher [70]. This is another limitation that suggests our soil carbon estimates may be conservative.

For our greenhouse gas emissions monitoring methods, it is important to underscore that agricultural soil emissions are highly spatio-temporally variable [81]. This variability is particularly high during acute management activities such as injecting manure. While the use of individual static chambers used for greenhouse gas emissions measurements may not capture the full range of emissions, our sampling methods are standard methods designed to try to account for spatio-temporal variability [47,49]. To address spatial variability, we placed five chambers randomly across each field to capture a range of field variability, and were careful to place chambers relative to acute management activities such that chambers covered the range of field conditions (e.g., placing chambers such that they incorporated soil affected by injection strips and soil not affected by injection strips). To address temporal variability, we sampled more frequently around acute management

activities (e.g., manure spreading or injecting events), and use annual GHG emissions averages to compare between the fields.

Our study is limited by the ecosystem services for which we had relevant data and the scale at which we monitored. While our study represents a more extensive in situ assessment of multiple ecosystem services than many, it would be strengthened by including important ecosystem services such as biodiversity. Our study is limited to the field scale and does not take into consideration the way farm management decisions about the landscape matrix, which would include fallow rotations buffers and unmanaged forest portions, which are likely to increase ecosystem service provisioning. Nor does our assessment include the intensively managed farm yard and manure storage portions of the farm, which are known to have high concentrations of nutrients and have high emissions and nutrient export potential [82].

Finally, our study is limited by the time period during which we collected data. Our dataset spans seven years, which is longer than most USDA funded grant periods, but as our farmer research partners observed, was too short a time to adequately understand how management regimes influence dynamic shifts in long-term ecosystem function.

4.6. Future Research and Implications

Our study provides a holistic cross-section snapshot of the implementation of two practices that are intended to improve environmental outcomes, but instead present tradeoffs, and this merits further exploration and investigation on many fronts. As our farmer-research partners pointed out, management is subject to change, as they learn about new tools and strategies that can enhance stewardship while keeping them in business. Our study demonstrates that changes to manure application practices can have strong impacts on GHG emissions and are an important place for farmers and research to work together to find practices that optimize nutrient availability to plants while also optimizing climate and clean water regulation. While our study did not find that practices enhanced climate regulation or water quality ecosystem services, our results point to the importance of investigating adjustments that would achieve those outcomes. This is especially important in light of the fact that farmers are motivated to adopt practices that have environmental co-benefits. Prior research indicates that timing of management can have a large effect on climate regulation and water quality outcomes, as can manure and nutrient application rates, as can the mix of cover crops species. These are important leverage points, where researchers must engage farmers in adaptive management through shared learning and iterative research trials. However, our study suggests that enhancements to ecosystem services are not always dominated by soil, crop and nutrient management. Soil texture and landscape features may have a dominating impact that limits the extent to which field management influences ecosystem services outcomes. This means that honing-in on agronomic leverage points for joint production of ecosystem services and farm viability must be accompanied by spatially explicit inquiry into the limits of potential BMPs. Long-term and replicated field-scale research is needed to identify the way site and soil characteristics interact with management to influence the supply of ecosystem services.

Research at the whole-farm scale that takes a similarly transdisciplinary and multifaceted approach to evaluating ecosystem services is needed to better understand the impact of agriculture on ecosystem services. Cultural ecosystem services are challenging to include, but are critical to understanding the way more transformative changes in agriculture influence the balance of ecosystem service supply.

Importantly, our study suggests that financial incentive and cost-share programs which support ecosystem service provisioning are critical to ensuring agricultural management adjustments that support society scale goals, especially if those changes come at a cost to the farmer. Our study also highlights that these conservation incentive programs, and new payment for ecosystem services programs, should incorporate the variable performance of practices. In light of our research, the case for public investment in payment for ecosystem services programs based on soil health metrics is hard to make, as we have

demonstrated that, in these trials, ecosystem services from healthy soils accrue primarily to the farm, and not society. As well, payment for ecosystem services programs must account for hard-to-measure pathways of impact on ecosystem services supply in order to achieve the impacts they aspire to. Unseen pathways dominating ecosystem service supply (subsurface hydrologic nutrient export, and soil surface GHG emissions) should be incorporated into program and policy advancements that aim to pay farmers for ecosystem services. If water quality payment for ecosystem services programs are designed based on the quantification of surface runoff impacts, they may be inadequately accounting for the majority of nutrient export which often takes place in the subsurface. Likewise, if programs pay farmers for carbon sequestration without quantifying GHG emissions, they may not be achieving the climate regulation impacts they espouse to. While this may be one of the most important implications of our study, there are limited data on subsurface phosphorus dynamics, and this represents an important research front in P impaired watersheds.

5. Conclusions

The pursuit of sustainable agriculture requires both a greater understanding of nuanced ecological outcomes attributed to changes in farm management, and the social factors that influence farmers' capacity and motivation to make changes. Our study identified tradeoffs in ecosystem services provisioning from two farm trials of best management practices. Our analysis demonstrates that it is not sufficient for understandings of ecosystem service supply to rest solely on the adoption of practices. Recommended practices do not universally enhance ecosystem services. To the contrary, we found that sometimes recommended practices may diminish the supply of ecosystem services. What emerges here is an understanding that outcomes from soil and nutrient management are nuanced and complex and are influenced by both site characteristics and small shifts in management. Similarly, increases in soil health indicators are not reliably linked to society scale ecosystem services, but can be more easily linked to agronomic, farm-scale benefits. Subsurface hydrologic nutrient export is poorly incorporated into understandings of clean water regulation used by farmers and policy, but may be the pathways of greatest impact on water quality. Similarly, greenhouse gas emissions from the soil surface are under-researched, but they can offset gains in soil carbon associated with soil building practices. Ecosystem services incentive programs that are performance-based could address the contextual differences of management effects, but need to account for these hard-to-measure pathways in order to be accurate.

Soil health and farm economics are important mediators influencing drivers, outcomes and feedbacks of farm decision making in this social ecological system. Cost-share incentive programs and financial motivations are significant determinants of farmers' management decisions alongside environmental stewardship in our two case study farms. Financial concerns and market patterns emerged as major limitations to management for environmental benefits. Overall, our research points to the need for more comprehensive understandings of agroecosystem performance that include hard-to-measure pathways for socially important outcomes, and the value of incentive programs to support changes in management that impart ecosystem services to public beneficiaries.

This paper documents environmental monitoring data that complicate the evidence base for best management practices in sustainable agriculture. We use the ecosystem services framework and complementary economic and social science data to put the biophysical data into socially relevant light, and in doing so, we demonstrate a holistic perspective on sustainable agriculture research. Employing a transdisciplinary ecosystem services case study approach offers a unique depth of inquiry. At the field scale and with a rich breadth of types of empirical data over multiple years, our study was able to identify tradeoffs among ecosystem services, leverage points for change, and relative levels of impact among nutrient flux pathways. The case study approach is limited in making broad inference, but is well suited to illustrate the nuances of the social-ecological system feedbacks and leverage points for decision makers and researchers.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su131810303/s1>. Table S1. Changes in soil health ratings, 2016 to 2018. Table S2. Changes in measured available water capacity, equivalent inches of rain and equivalent gallons of available water per acre from soil tests in each field 2016 to 2018. Table S3. Soil organic matter content by field for 2012 and 2018, and estimates of carbon sequestration for each agroecosystem in the top 15 cm of soil. Table S4. Detailed account of fuel consumption associated with tractor tasks for all field management, and equivalent MT CO₂ per hectare. Table S5. Summary of annual diesel fuel consumption for each field and equivalent MT CO₂ per hectare. Table S6. Average daily and annual fluxes of N₂O and CO₂ measured from the soil surface from April to November for years 2016, 2017 and 2018. Table S7. Mean event runoff volume and nutrient load export for all rain events that generated runoff in the EOF stations, by paired watersheds, for control and treatment periods. Table S8. Mean difference in water quality parameters between CCMIRT field and control corn field, for the calibration and treatment periods. Table S9. Dry matter yield from aerated hay field trial in tons per acre, differentiated by cut. Table S10. Economic comparison of cost and income in paired corn fields based on custom rates and farmers records, including annual difference in gross margin per acre, and overall average difference in gross margin between fields. Table S11. Economic comparison of cost and income in paired hay fields based on custom rates and farmers records, including annual difference in gross margin per acre, and overall average difference in gross margin between fields. Table S12. Detailed account of the expenses and revenues for each field. Table S13. Change in soil health indicators for all fields, 2016–2018. Table S14. Measured soil health parameters for all fields and years, conducted by the Cornell Comprehensive Assessment of Soil Health (CASH). Figure S1. Change in biological soil health indicators, 2016 to 2018. Figure S2. Change in chemical soil health indicators for all fields, 2016 to 2018. Figure S3. Change in physical indicators of soil health on all fields, 2016 to 2018. There is a notable change in directionality of available water capacity between control and treatment for both BMP paired field trails. Aggregate stability increased for both perennial hay fields and decreased for both annual corn fields. Figure S4. Soil texture assessment of soil samples from top 15 cm of soil profile for all fields in 2018. Corn field control and treatment fields are similar. Sand content in the hay field BMP treatment is greater than the control field. Figure S5. Bivariate regression between discharge generated in the two fields during the calibration period to assess similarity in hydrologic response to rainfall. File S1. Interview protocol and questions.

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