Field scale soil health scenarios. Vermont Payment for Ecosystem Services Technical Report #2

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The University of Vermont

Field scale soil health scenarios

Vermont Payment for Ecosystem Services Technical Research Report #2

Prepared for the Vermont Soil Health and Payment for Ecosystem Services Working Group

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GUND INSTITUTE FOR ENVIRONMENT

THE UNIVERSITY OF VERMONT EXTENSION

Executive Summary

This report illustrates how changes in management on Vermont farms can influence soil health metrics at the field scale. We've used regionally relevant science-based scenarios to demonstrate how selected soil health metrics that are associated with ecosystem services could change on farms in response to management practices at the field scale. These field scale management scenarios demonstrate that many practices in use by farmers in Vermont can have positive impacts on the soil health indicators of interest to the Vermont Soil Health & Payment for Ecosystem Services Working Group. The scenarios document potential for tradeoffs among soil health properties. Specifically, some of the scenarios illustrate how bulk density and compaction can worsen in instances when other soil health properties improve. Long-term research that measures multiple indicators of soil health and ecosystem services on recommended soil health management practices in Vermont is needed to support the evidence-base for soil health and ecosystem services incentive programs.

The soil health outcomes from specific scenarios described in this report include:

Scenario #1: Best Management Practice Corn (No-till and Cover Crop)

- In replicated plot research on rocky silty loam soil, no-till & cover crop practices in corn silage systems resulted in significantly higher aggregate stability, organic matter, soil respiration, and an overall higher CASH soil health score than without these conservation practices.

Scenario #2: Corn hay rotation

- In long term replicated plot research on silt loam soil, organic matter, aggregate stability and soil respiration were all significantly greater in a corn-hay rotation compared to continuous corn. Soil health indicators overall were best in the rotation treatment in its first year out of hay.

Scenario #3a: Transition from annual cropping to rotational grazing

- In a transition from annual cropping to perennial pasture on clay loam soil, bulk density worsened and biological soil health indicators increased (β-glucosidase activity, microbial biomass carbon and potentially mineralizable N).

Scenario #3b: Restoring soil function with management-intensive grazing rotation

- Organic matter increased 2.75% over four years in a local management-intensive grazing system on clay and silty clay soils..

Scenario #4a: Vegetables with a soil building cover crop rotation

- A soil building cover crop rotation in a vegetable production system on silt loam soil had higher organic matter, surface hardness, aggregate stability, and active carbon than a continuously cropped system after 3-4 years.

Scenario #4b: Vegetable production with reduced tillage

- Reduced and no tillage treatments in vegetable plots on silt loam soil significantly increased aggregate stability and surface hardness after 3-4 years, though no significant difference in organic matter was detected.

Scenario #4c: Fertility practices in organic vegetable systems

- High compost rate treatments on a silty clay loam soil increased soil carbon and decreased bulk density in organic vegetable systems. High compost treatments also significantly reduced runoff, increased water holding capacity and demonstrated reduced nutrient loading.

Scenario #5a: Hayland with broadcast manure compared to incorporation with aerator

- A long term paired field trial on haylands on a Vermont farm with clay soils evaluated the use of an aerator prior to broadcasting manure. Overall CASH soil health scores increased in both fields, but to a greater extent in the aerated field. Organic matter, aggregate stability and respiration increased in both fields, more so in the control field.

Scenario #5b: Hayland with injected manure, with and without inhibitor

- In a randomized complete block treatment study of haylands on silt loam soils, manure application methods, nitrogen sources and inhibitor application did not influence N_2O or CO_2 fluxes from the soil surface.

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Introduction

This report illustrates how changes in management on Vermont farms can influence soil health metrics at the field scale. The report was written based on input from the Vermont Soil Health and Payment for Ecosystem Services Working Group and is intended to be informative and illustrative for members of the group.

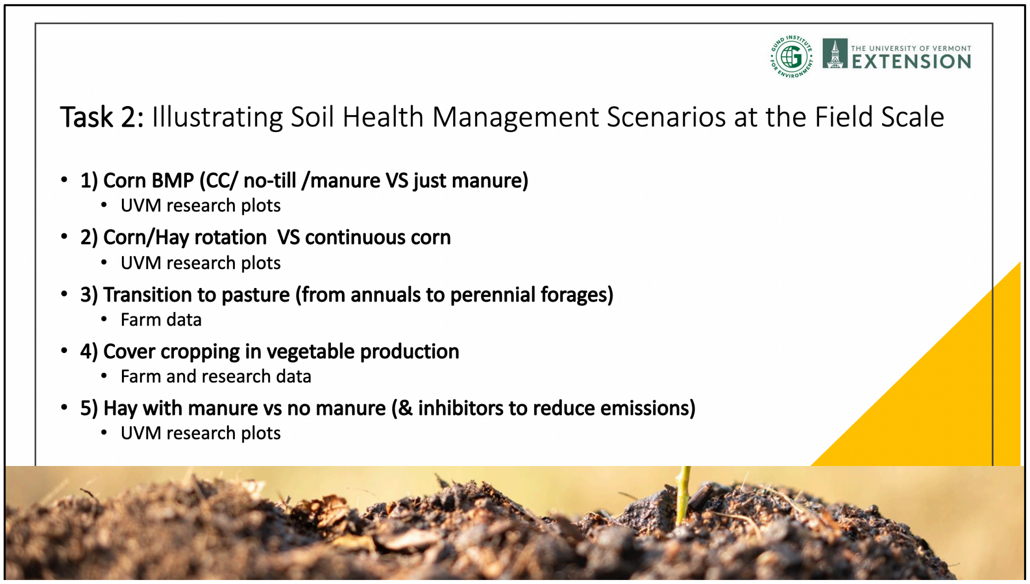
We use regionally relevant science-based scenarios to demonstrate how soil health metrics and associated ecosystem services could change on farms in response to management changes at the field scale. Although the data presented is science-based, it is important to note that much of it is not generalizable. Measurable soil health outcomes are influenced by existing environmental and site conditions, management history, and soil texture, and are thus incredibly context dependent. Still, in light of this caveat, it is important for working group members to understand examples of how soil health metrics are influenced by soil management in Vermont. Whenever possible, we drew from research conducted in Vermont, or within the northeast region. Much of the information is based on studies that have been published in peer reviewed journals or technical reports.

For some soil health indicators it can take 5 to 7 years before changes are observed, and many of the studies were limited because they were short term (2 to 3 years). Some of the studies used replicated plot trials in their experimental design to establish statistical significance, while others tracked changes over time.

The information in this report is organized around the soil health metrics that were selected as indicators of ecosystem services by the working group’s soil health subcommittee in 2021. These indicators are organic matter, aggregate stability, bulk density, greenhouse gas emissions and soil biodiversity. In this report, we first describe our approach briefly. Then, a brief description of the overall findings and a summary table highlight the way each scenario influenced the soil health metrics of interest. Finally, each scenario is described individually. An appendix shares the Comet Planner reports used to supplement the information on greenhouse gas emissions.

Methods

In October of 2021 PES Working Group members filled out a survey to identify the soil health scenarios that should be included in this report, and shared sources of data that could be used for the scenarios. The results of the survey were organized thematically, and then presented back to the Working Group for further feedback in an iterative manner. The final list of scenarios to be included in the report was determined in collaboration with the working group on November 16th 2021 with suggested data sources (figure 1).



Task 2: Illustrating Soil Health Management Scenarios at the Field Scale

- **1) Corn BMP (CC/ no-till /manure VS just manure)**
  - UVM research plots
- **2) Corn/Hay rotation VS continuous corn**
  - UVM research plots
- **3) Transition to pasture (from annuals to perennial forages)**
  - Farm data
- **4) Cover cropping in vegetable production**
  - Farm and research data
- **5) Hay with manure vs no manure (& inhibitors to reduce emissions)**
  - UVM research plots

Figure 1. Preliminary list of soil health scenarios agreed upon for the report, as presented to the PES Working Group on November 16th.

For the first two scenarios, robust research data from UVM Extension's Borderview Research Farm was available which included most of the soil health metrics of interest. For the other scenarios, available studies often included only some of the soil health metrics of interest. Thus, we employed literature reviews and conversations with local experts to identify additional data that would provide a more complete perspective on how management can realistically influence soil health metrics at the field scale in Vermont. This process revealed a need for research on how organic vegetable production and pasture systems influence soil health and greenhouse gas emissions, as well as a dearth of information on soil biodiversity. Due to the lack of comprehensive studies that included multiple indicators for some systems, we included additional scenarios. Nine scenarios were ultimately included in this final report.

Greenhouse gas emissions data was rarely included in the referenced studies, so the NRCS Comet Planner tool was used to identify the directionality of impact on nitrous oxide emissions, carbon dioxide emissions and net carbon sequestration. The Comet Planner reports used for this are included in Appendix A.

Discussion

Overall, the available data we reviewed demonstrates that recommended practices which farmers are already using in Vermont can have measurably positive impacts on indicators of soil health. Different management practices effect different soil properties. In the scenarios, reduced tillage generally increased measures of aggregate stability. Applications of compost improved bulk density. Scenarios that featured increases in carbon-based inputs and residues, such as compost applications and cover cropping, demonstrated measurable increases in soil organic matter.

Organic matter, as a foundation of healthy soil was either improved in the scenarios we reviewed or demonstrated no measurable change over the time period of the studies. Improvements in soil carbon are known to take at last 5 to 7 years to detect, and this evidence should remind the PES Working Group to design a program that takes the long-term nature of investing in soil health into account.

Across the data we reviewed for this report, in no case were all of the indicators of interest measured in a single study, and in no case were all of the measured soil health indicators improved by a management scenario (Table 1). In some cases, the scenarios document potential tradeoffs among soil health properties. In particular, we observed many scenarios where practices were implemented and bulk density worsened-- this indicates soil compaction may need careful attention and greater educational focus within or alongside a PES program.

Greenhouse gas emissions were rarely measured, but the Comet Planner tool provided estimates of directionality and relative impact on overall climate regulation ecosystem services for all the scenarios we reviewed. Long-term research that measures multiple indicators of soil health and ecosystem services is needed to support the evidence-base for soil health and ecosystem services programs. This research could be built into the monitoring and verification aspects of a soil health PES program.

In our research for this report, we came across a dearth of studies relevant to the northeast on soil health and ecosystem services in vegetable production and pasture systems, as well as greenhouse gas emissions and comprehensive studies that included multiple indicators. Replicated plot research that includes a large suite of soil health metrics should be conducted to fill knowledge gaps about promising practices and inform the recommendations of a PES program.

Scenarios

Soil Health Scenario #1: Best Management Practice Corn (No-till and Cover Crop)

Scenario description	
Title of scenario	Best Management Practice Corn (No-till and Cover Crop)
Source of information	UVM Extension Northwest Crops and Soils Team Report based on research plots at Borderview Farm: 2020 Integrating Cover Crops and Manure into Corn Silage Cropping Systems by Dr. Heather Darby, UVM Extension Agronomist and Sara Ziegler, John Bruce, Ivy Krezinski, Rory Malone, and Lindsey Ruhl
Location and soil type	Borderview Research Farm in Alburgh, Vermont Benson rocky silt loam soil.
Land use and management history	Prior to implementation of this research, the area was planted with a variety of annual crops in a conventional tillage operation.
Detailed description of management/treatments and study design	The experimental design was a randomized complete block with replicated treatments of corn grown in various cropping systems. A best management practices (BMP) scenario of no-till and cover-cropped corn was grown alongside a 'business as usual' scenario with conventional tillage and no cover crop. Both treatments had spring applied manure. Other management treatments were included in this study but not described in this summary. Plots were 10' x 40' and replicated four times over three years. There were slight differences in dates, fertilizer application rates, and herbicide termination across the three years. In general, these were the order of events: Manure was surface applied to spring manure plots in early to mid-May at a rate of 6,000 gal/acre (+/- 200 gal) each year of the trial. In the conventional plots, manure was immediately incorporated using a disc harrow. Winter rye was planted at a rate of 100 lbs ac^{-1} at the end of September. In the spring, soil samples were collected for nitrate and soil health analysis with the Cornell Assessment of Soil Health (CASH) test package. Depending on the year, cover crop ground cover, height, and biomass was measured in late April to early May. Cover crops were terminated with herbicide in the no-till plots and in conventionally managed plots the cover crops were incorporated with a disc harrow. Corn was planted between mid-May and early June with a John Deere 7500 no-till corn planter at a rate of 34,000 seeds ac^{-1}. All corn plots received starter fertilizer. Soil samples were collected for PSNT analysis in the summer. Prior to corn harvest, corn populations were counted and samples were collected for CSNT (corn stalk nitrate test). Corn was harvested between early and mid-September. Samples were collected for yield and quality analysis by NIR.
Time period of data collection	3 years, Between fall of 2017 and the fall of 2020
Measured soil health outcomes	
Summary of influence on soil health	BMP practices resulted in higher aggregate stability, organic matter, soil respiration, and an overall higher CASH soil health score than business as usual (83.4, very high functioning vs 78.0, high functioning).
Directionality and measured extent of impact on selected soil health indicators:	

Organic matter	Over three years the accumulated effects were a net increase of 0.3% organic matter more in the BMP treatment than the conventional treatment. In 2020 the conventional, 'business as usual' treatment had 4.07% organic matter, and the BMP treatment had 4.37% organic matter.
Bulk density	Bulk density was not measured, but penetrometer data is used as a proxy. Penetrometer data in 2020 was not statistically significantly different among the treatments.
Aggregate stability	Over three years the accumulated effects were a net increase of 11.1% more in water stable aggregates in the BMP treatment than the conventional treatment. In 2020 the conventional, 'business as usual' treatment had 29.9% stable aggregates, and the BMP treatment had 41.0% stable aggregates.
N_2O & CO_2 emissions	Not measured. However, NRCS Comet Planner tool estimates that non legume cover crops cause small increases in nitrous oxide emissions that are offset by CO_2 reductions and carbon sequestration. It also estimates that no-till reduces nitrous oxide emissions. Considering, N_2O emissions, CO_2 emissions and carbon sequestration together, Comet Planner estimates the combination of cover cropping and no-till sequester a net equivalent of 0.68 tonnes CO_2e per acre per year.
Soil biodiversity	No measure of biodiversity was collected. However, indicators of biological activity were collected. Over three years the accumulated effects were a greater net increase of 0.170 mg CO_2 g soil^{-1} in soil respiration in the BMP treatment than in the conventional treatment. In 2020 respiration in the conventional, 'business as usual' treatment measured : 0.567 CO_2 g soil^{-1} , and in the BMP treatment it was 0.737 CO_2 g soil^{-1} .
Additional Information	
Other data (yield, etc.)	Interactions: The 'business as usual' treatment increased in yield in 2019, despite cool wet spring conditions that delayed planting, before returning to a level similar to 2018 in 2020. In comparison, yields in from the BMP treatment had relatively steady yields, regardless of deviations in weather. While there was no significant difference in nitrate availability in the spring, PSNT levels in the summer were lower in the BMP scenario, which may have impacted yields. Overall, the 'business as usual' treatments produced an average of 21.6 tons ac^{-1}. On average, that is 3.3 tons ac-1 more than the BMP treatment (18.3 tons ac^{-1}). Crude protein was 0.65% higher in the 'business as usual' (9.50%) than the BMP (8.85%) treatment. There were no significant difference in other commonly measured quality metrics. It is important to note that in this study, aggregated over three years, higher soil health does not necessarily translate to higher yields or yield with higher quality.
Data limitations	Data was averaged over three years to reduce year-to-year variability. 2020 is the third year in no-till for the no-till plots. It may take several years before full effects of no-till on soil health is realized, and the averaging approach to addressing interannual variability in soil measurements limits the degree to which we can see improvements over time. This data reflects measurements that are subject to influence by soil type, environment, timing, and management history and therefore may not be representative of many fields.
References	Full report of the study is available. Darby, Heather et al., (March 2021). Integrating Cover Crops and Manure into Corn Silage Cropping Systems. University of Vermont Extension, Northwest Crops and Soils Program. https://www.uvm.edu/sites/default/files/Northwest-Crops-and-Soils-Program/2020%20Research%20Reports/2020_Integrating_Cover_Crops_and_Manure_into_Corn_Silage_Cropping_Systems_updated.pdf

Soil Health Scenario #2: Corn hay rotation

Scenario description	
Title of scenario:	Corn hay rotation
Source of information	UVM Extension Northwest Crops and Soils Team Report based on long term research plots at Borderview Farm: 2020 Corn Cropping Systems to Improve Economic and Environmental Health.
Location and soil type:	Borderview Research Farm in Alburgh, Vermont Amenia silt loam, 0-2% slope
Land use and management history:	Long term research plots since 2008, previously in corn or alfalfa/fescue
Detailed description of management or treatments and study design:	Replicated treatment plots monitored soil health in long-term corn-hay rotations alongside a continuous tilled corn treatment, and other corn cropping treatments. The experimental design was a randomized complete block with replicated treatments of corn grown in various cropping systems. No manure was used in this trial. Two corn-hay rotation treatments, in a 5-year hay to 5-year corn rotation, were part of this study. The only difference between them being that they are on different years in the rotation. In 2020, one of the corn-hay treatments rotated into hay from corn, and the other from corn to hay. All plots in the trial received a spring fertilizer application of 300 lbs ac^{-1} of 19-19-19. The continuous corn is plowed in early May. In year one rotation plots, after the first perennial forage cut, herbicide was sprayed to terminate the perennial forage and then seeded with corn. Corn was seeded in 30” rows at 34,000 seeds ac^{-1} with a 92 days variety. At planting, 200 lbs ac^{-1} of an 10-20-20 starter fertilizer was applied to all corn plots. For rotation into sod, treatments that were planted in corn since 2014 were tilled in early May and planted the next day with a perennial forage mix of 60% alfalfa and 40% tall fescue at a rate of 20 lbs ac^{-1}. Corn plots received spring herbicide weed control and were side-dressed with broadcast nitrogen in June at rates according to PSNT-based recommendations. Soil health was measured annually using the Cornell Assessment of Soil Health test and bulk density was measured to 30 cm depth in each plot in year 2021. Forage yield and quality were assessed each year for both annual corn and perennial forage.
Time period of data collection:	Research on this trial has spanned 11 years, 2012 – 2021
Measured soil health outcomes	
Summary of influence on soil health:	Organic matter, aggregate stability and soil biological activity (measured through respiration) were all significantly greater in the corn-hay rotation compared to continuous corn. Soil health indicators overall were best in the rotation treatment in its first year out of sod. Bulk density was not different between treatments.
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	Corn-hay rotation had a net additional 0.25% to 1.22 % organic matter compared to continuous corn treatment (significant to p=0.1). In 2021 organic matter content was 3.31% in the continuous corn treatment, 4.53% in the rotation treatment that was coming out of 5 years hay and 3.55% in the rotation treatment that was coming out of 5 years corn. No manure was added in this trial, so organic matter increases are primarily due to crop residues.
Bulk density	No significant difference observed between treatments for bulk density samples collected in 2021.

Aggregate stability	Corn-hay rotation had a net additional 9.4% to 41.3 % aggregate stability compared to continuous corn treatment (significant to p=0.1). In 2021 aggregate stability was 33.3% in the continuous corn treatment, 74.6% in the rotation treatment that was coming out of 5 years hay and 42.7% in the rotation treatment that was coming out of 5 years corn.
N_2O & CO_2 emissions	Not measured. However, NRCS Comet Planner estimates that adding perennial crop rotation reduce nitrous oxide emissions.
Soil biodiversity	No measure of biodiversity was collected. However, indicators of biological activity were collected. Corn-hay rotation had an additional 0.489 to 0.623 CO_2 g soil^{-1} respiration compared to continuous corn treatment (significant to p=0.1). In 2021 respiration was 0.537 CO_2 g soil^{-1} in the continuous corn treatment, 1.16 CO_2 g soil^{-1} in the rotation treatment that was coming out of 5 years hay and0.671 CO_2 g soil^{-1} in the rotation treatment that was coming out of 5 years corn.
Additional Information	
Other data (yield, etc.)	No significant difference between corn yields was detected. Higher dry matter content and quality characteristics were detected for the corn in its first year out of hay, but could have been attributed to a later planting date that was not impacted by late frost a compared to the other corn plots. Other corn system treatments in this study included tilled corn with cover crop, no-till corn, and no-till with winter cover crop.
Data limitations	This data reflects measurements that are subject to influence by soil type, environment, timing, and management history and therefore may not be representative of all fields.
References:	A full report of the trial results is available online: Darby, H., Ruhl, L., Malone, R and S. Ziegler. (January 2021). 2020 Corn Cropping Systems to Improve Economic and Environmental Health. University of Vermont Extension, Northwest Crops and Soils Program. https://www.uvm.edu/sites/default/files/Northwest-Crops-and-Soils-Program/2020%20Research%20Reports/2020_Corn_Cropping_Systems_Report_VIRECA.pdf

Soil Health Scenario #3a: Transition from annual cropping to rotational grazing

Scenario description	
Title of scenario	Transition from annual cropping to rotational grazing
Source of information	Shawver, C. J., Ippolito, J. A., Brummer, J. E., Ahola, J. K., & Rhoades, R. D. Soil health changes following transition from an annual cropping to perennial management-intensive grazing agroecosystem. *Agrosyst Geosci Environ*. 2021; 4:e20181. https://doi.org/10.1002/agg2.20181
Location and soil type	Colorado State University Agricultural Research, Development and Education Center, Fort Collins, CO 80524. Clay loam soil.
Land use and management history	Pasture rotational grazed since 2017, converted to perennial pasture 2016. Tilled cropping system (corn, silage, dry beans, alfalfa) prior to that.
Detailed description of management/treatments and study design	The field was planted with grass-legume mix in 2016 and cross drilled with legumes in 2017. The field was 82 hectares with a central pivot irrigation system, which was split into 32 paddocks for grazing with animals that were moved every 1-4 days to leave 50% forage behind. Soil samples were collected on 15 randomly selected paddocks (30 soil cores per replicate), in May 2017 and again in May 2018. The Soil Management Assessment Framework (SMAF) assessment tool was used.
Time period of data collection	2017-2018
Measured soil health outcomes	
Summary of influence on soil health	Physical soil health indicators decreased between 2017 and 2018 (bulk density increased, water stable aggregates did not change). Biological soil health indicators increased between 2017 and 2018 (β-glucosidase activity, microbial biomass carbon and potentially mineralizable N).
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	No change in soil organic carbon was detected between years
Bulk density	Bulk density increased between 2017-2018.
Aggregate stability	No change in water stable aggregates was detected between years.
N_2O & CO_2 emissions	Not measured. However, NRCS Comet Planner estimates that the conversion to forage and biomass plantings would reduce nitrous oxide emissions.
Soil biodiversity	Increases in soil biological activity (β-glucosidase activity, microbial biomass carbon and potentially mineralizable N) were observed.
Additional Information	

Other data (yield, etc.)	Reduction in nutrient soil health indicators between 2017-2018 due to reduction in extractable P concentrations, although extractable K concentrations increased over time.
Data limitations	This experiment was conducted in the arid climate of Colorado, so has limited transferability to Vermont. Data only shows the impact of one grazing season, because measurements were taken before grazing began in May 2017 and then before the second grazing year began in May 2018.
References	Shawver, C. J., Ippolito, J. A., Brummer, J. E., Ahola, J. K., & Rhoades, R. D. Soil health changes following transition from an annual cropping to perennial management-intensive grazing agroecosystem. *Agrosyst Geosci Environ*. 2021; 4:e20181. https://doi.org/10.1002/agg2.20181 Contosta, A. R., Arndt, K. A., Campbell, E. E., Grandy, A. S., Perry, A., & Varner, R. K. (2021). Management intensive grazing on New England dairy farms enhances soil nitrogen stocks and elevates soil nitrous oxide emissions without increasing soil carbon. *Agriculture, Ecosystems & Environment*, *317*, 107471.

Soil Health Scenario #3b: Restoring soil function with management-intensive grazing rotation

Scenario description	
Title of scenario	Restoring soil function with management-intensive grazing rotation
Source of information	UVM Extension, Center for Sustainable Agriculture, Pasture Program, based on 5-year research at Philo Ridge Farm.
Location and soil type	Philo Ridge Farm in Charlotte, Vermont, 05445 Vergennes and Covington clay soils. Clay & silty clay
Land use and management history	Until 2012, Philo Ridge Farm (former Foote Farm, owned by the Foote family for six generations) operated as a conventional dairy known as Foote Farm, where fields were rotated with corn, alfalfa, and hay. In 2012, 400-acre Philo Ridge Farm began an ecological farming project, and a few years later, the farm started to incorporate diversified agricultural practices working to improve the pastures utilizing high-stock density grazing on every pasture to produce meat, wool, fruits and vegetable crops.
Detailed description of management/treatments and study design	No known soil amendments, other than high-stock density grazing animal effect was applied between 2015-2017. Each animal unit, AU can return in average about 250 lb of N and over 100 lb of P, K and Ca respectively via manure and urine, per year. Grazing animals, grazed 1/3 to 1/2 of the pre-grazing forage of each paddock subdivision for one day, resting until the pasture recovered between 20 and 45 days. On-farm compost application started to be applied in selected areas of hayfield(s) after 2017. Repeated measurements of 25 cm-deep soil cores (x ~50 cores per field) were taken from every hay and grazing fields of the farm, during 2015, 2017, 2019 and 2021. Soil chemistry was assessed for pasture and hay at the University of Vermont Ag. Testing Lab and soil biological diversity at Earth Fortifications Laboratory. Comprehensive measurements of soil biological diversity (ciliates, flagellates, amoeba, mycorrhizae, active bacteria, total bacteria, active fungi, total fungi, fungi hyphae diameter, bacteria/fungi ratio) was collected from every field, but not reported at this time. Bulk density and penetrometer data on one field was measured, but is not reported at this time. One hayfield that has never been grazed will be used a control comparison when the study is published, but is not reported here.
Time period of data collection	Whole farm soil data collection spanned from 2015 to 2021, data collected every 2 years (2015; 2017; 2019, and 2021).
Measured soil health outcomes	
Summary of influence on soil health	Organic matter, and other soil macro and micronutrients, and biological activity changed after applying management-intensive grazing between 2015 and 2019 (2021 data still pending).
Directionality and measured extent of impact on selected soil health indicators:	

Organic matter	Preliminary data shows an increase of soil organic matter across the farm of 1.91% between 2015 and 2017, 0.84% between 2017 and 2019, (2.75% between % between 2015 and 2019). 2021 data has not been analyzed yet, as soil tests just arrived from the soil's laboratory.
Bulk density	Not reported.
Aggregate stability	Not reported.
N_2O & CO_2 emissions	Not measured. Not enough information exists to project the impact of rotational grazing on nitrous oxide emissions, but recent research on organic pastures in the Northeast suggests N_20 emissions can offset soil carbon gains in some, but not all cases (Contosta et al., 2021).
Soil biodiversity	Not reported.
Additional Information	
Other data (yield, etc.)	Significant difference in organic matter increase were found over time in some of the fields, after management intensive grazing was implemented across the farm in 2016, especially on hayfields, old corn-alfalfa fields and other grazing fields was detected.
Data limitations	What is reported here from this study is longitudinal observational data, tracking indicators over time, and does not include comparisons to a control treatment. This data reflects measurements that are subject to influence by soil type, environment, timing, and management history and therefore may not be representative of all fields.
References	Data and information based 2015-2021 UVM Extension, Juan Alvez field experiments at Philo Ridge Farm; currently working on manuscript preparation. Contact Juan with any questions. Juan.Alvez@uvm.edu

Soil Health Scenario #4a: Vegetables with a soil building cover crop rotation

Scenario description	
Title of scenario	Vegetables with a soil building cover crop rotation
Source of information	Idowu, O. J., Van Es, H. M., Abawi, G. S., Wolfe, D. W., Schindelbeck, R. R., Moebius-Clune, B. N., & Gugino, B. K. (2009). Use of an integrative soil health test for evaluation of soil management impacts. *Renewable Agriculture and Food Systems*, *24*(3), 214-224.
Location and soil type	The study was conducted at the Gates experimental farm in Geneva, NY on Kendaia silt loam and Lima silt loam soils.
Land use and management history	The soil had been in continuous vegetable rotation as part of a commercial operation for many years.
Detailed description of management/ treatments and study design	The study site consisted of 72 plots over 6 hectares with three tillage, three cover crop and two rotation treatments. Tillage treatments included no till (NT), zone-till (ZT), and a full till scenario of both mouldboard and discing (PT). The three cover crop treatments were no cover, rye and vetch. The first rotation involved continuous high-value vegetable cropping, while the second rotation incorporated season-long soil-building crops. Cover crops were established in early fall and killed with glyphosate in the spring. A zone builder with a deep ripping shank to 0.3 m established the zone tillage (ZT) treatments each spring with 0.015 m wide planting zones. The PT treatment used mouldboard plowing and discing each spring to prepare a seedbed. The continuous cropping sequence was bean – beet – sweet corn – cabbage. The soil building rotation was bean – field corn – clover/barley – sweet corn – bean. To isolate the impact of rotations for this scenario report, we selected data from the PT (mouldboard and discing) and no-cover treatments for both rotations to highlight the impact of the rotation on soil health indicators. The tillage treatment impacts are highlighted in Scenario 4b.
Time period of data collection	The experiment was established in 2003 and soil samples were collected in 2006 and 2007
Measured soil health outcomes	
Summary of influence on soil health	After 3-4 years in different rotations organic matter, surface hardness, aggregate stability, active carbon were higher in the soil building rotation.
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	At the end of the study organic matter content was higher by 0.2% in the soil building rotation. Organic matter was 2.2% in the continuous vegetable treatment, and 2.4% in the soil building rotation treatment.
Bulk density	Bulk density was not measured, but penetrometer data is used as a proxy. Surface and subsurface hardness were higher in the soil building rotation than the continuous cropping plots at the end of the experiment. At the end of the experiment, surface hardness in the continuous vegetable treatment was 0.85 Mpa and 1.19 Mpa in the soil building rotation treatment. Subsurface hardness in the continuous vegetable treatment was 1.90 Mpa and 2.13 Mpa in the soil building rotation treatment.
Aggregate stability	At the end of the experiment, aggregate stability was 5.1% higher in the soil building treatment than in the continuous cropping treatment. Aggregate stability in the continuous vegetable treatment measured at 14.4% in the final year, and was 19.5% in the soil building rotation treatment.

N_2O & CO_2 emissions	Not measured. However, NRCS Comet Planner tool estimates that perennial crop rotations reduce nitrous oxide emissions.
Soil biodiversity	Soil biodiversity was not measured but active carbon can be used as an indication of biological activity. At the end of the experiment active carbon level were similar, but slightly higher in the soil building rotation. Active carbon in the continuous vegetable treatment was 516 mg/kg, and in the soil building rotation treatment was 539 mg/kg.
Additional Information	
Other data (yield, etc.)	The experiment identified significant impacts of cover crops treatments on surface hardness and potentially mineralizable nitrogen, and suggested that longer term studies would be needed to detect the impact of covers crops on other soil health indicators. Tillage had significant effects on many indicators, which are summarized in Soil Health scenario 4b.
Data limitations	The 72 plot experiment was complex and the rotation treatments were not evaluated against each other for significant differences. Thus, the implications of this observation are limited, but useful for illustration. The use of glyphosate to kill down cover crops does not reflect dominant management trends among vegetable growers in Vermont. Additionally, some soil health outcomes, especially soil organic matter, take a long time to show detectable changes and this study may have been to short (3-4 years) to capture that.
References	Idowu, O. J., Van Es, H. M., Abawi, G. S., Wolfe, D. W., Schindelbeck, R. R., Moebius-Clune, B. N., & Gugino, B. K. (2009). Use of an integrative soil health test for evaluation of soil management impacts. *Renewable Agriculture and Food Systems*, *24*(3), 214-224.

Soil Health Scenario #4b: Vegetable production with reduced tillage

Scenario description	
Title of scenario	Vegetable production with reduced tillage
Source of information	Idowu, O. J., Van Es, H. M., Abawi, G. S., Wolfe, D. W., Schindelbeck, R. R., Moebius-Clune, B. N., & Gugino, B. K. (2009). Use of an integrative soil health test for evaluation of soil management impacts. *Renewable Agriculture and Food Systems*, *24*(3), 214-224.
Location and soil type	The study was conducted at the Gates experimental farm in Geneva, NY on Kendaia silt loam and Lima silt loam soils.
Land use and management history	The soil had been in continuous vegetable rotation as part of a commercial operation for many years.
Detailed description of management/ treatments and study design	The study site consisted of 72 plots over 6 hectares with three tillage, three cover crop and two rotation treatments. Tillage treatments included no till (NT), zone-till (ZT), and a full till scenario of both mouldboard and discing (PT). The three cover crop treatments were no cover, rye and vetch. The first rotation involved continuous high-value vegetable cropping, while the second rotation incorporated season-long soil-building crops. Cover crops were established in early fall and killed with glyphosate in the spring. A zone builder with a deep ripping shank to 0.3 m established the zone tillage (ZT) treatments each spring with 0.015 m wide planting zones. The PT treatment used mouldboard plowing and discing each spring to prepare a seedbed. The continuous cropping sequence was bean – beet – sweet corn – cabbage. The soil building rotation was bean – field corn – clover/barley – sweet corn – bean.
Time period of data collection	The experiment was established in 2003. Soil samples were collected in 2006 and 2007.
Measured soil health outcomes	
Summary of influence on soil health	Reduced tillage treatments significantly increased aggregate stability and surface hardness. After 3-4 years, no significant difference in organic matter was detected in this study. Active carbon was significantly reduced in the no till treatment only in the continuous rotation.
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	No significant differences in organic matter were detected in this study. At the end of the study, organic matter in the full tillage treatment was 2.2% in the continuous rotation, and 2.4% in the soil building rotation. Organic matter in the zone tillage treatment was 2.1% in the continuous rotation, and 2.0% in the soil building rotation. Organic matter in the no tillage treatment was 1.9% in the continuous rotation, and 2.2% in the soil building rotation.
Bulk density	Bulk density was not measured, so penetrometer data is reported as a proxy. Surface hardness was significantly higher in the no till than the other two tillage treatments in the soil building rotation ($p<.01$), and significantly higher in zone till than full till in the continuous rotation. Surface hardness in the full tillage treatment was 0.85Mpa in the continuous rotation, and 1.19Mpa in the soil building rotation. Surface hardness in the zone tillage treatment was 1.10Mpa in the continuous rotation, and 1.20Mpa in the soil building rotation. Surface hardness in the no tillage treatment was 0.99Mpa in the continuous rotation, and 2.01Mpa in the soil building rotation.

	No significant difference was detected in subsurface hardness. Subsurface hardness in the full tillage treatment was Mpa in the continuous rotation, and Mpa in the soil building rotation. Subsurface hardness in the zone tillage treatment was Mpa in the continuous rotation, and Mpa in the soil building rotation. Subsurface hardness in the no tillage treatment was Mpa in the continuous rotation, and Mpa in the soil building rotation.
Aggregate stability	Aggregate stability was significantly higher in the zone tillage treatment continuous rotation, and the no till treatment was significantly higher in aggregate stability in the soil building rotation ($p<0.05$). Aggregate stability in the full tillage treatment was 14.4% in the continuous rotation, and 19.5% in the soil building rotation. Aggregate stability in the zone tillage treatment was 19.8% in the continuous rotation, and 19.8% in the soil building rotation. Aggregate stability in the no tillage treatment was 16.0% in the continuous rotation, and 26.4% in the soil building rotation.
N_2O & CO_2 emissions	Not measured. However, NRCS Comet Planner tool estimates that reduced and no-till decrease nitrous oxide emissions.
Soil biodiversity	No indicator of biological diversity was monitored. The best indicator of biological activity used in this study was active carbon. Active carbon in the full tillage treatment was 516mg/kg in the continuous rotation, and 539mg/kg in the soil building rotation. Active carbon in the zone tillage treatment was 550mg/kg in the continuous rotation, and 509mg/kg in the soil building rotation. Active carbon in the no tillage treatment was 437mg/kg in the continuous rotation, and 553mg/kg in the soil building rotation. Active carbon was significantly reduced in the no till treatment only in the continuous rotation.
Additional Information	
Other data (yield, etc.)	Potentially mineralizable nitrogen, phosphorus, potassium and zinc were significantly higher in the zone tillage treatment in the continuous cropping rotation.
Data limitations	Replicated plot research is capable of detecting the significant impacts of management on soil health outcomes. However, some soil health outcomes, especially soil organic matter, take a long time to show detectable changes and this study was to short (3-4 years) to capture that. Additionally, the use of glyphosate to kill down cover crops does not reflect dominant management trends among vegetable growers in Vermont.
References	Idowu, O. J., Van Es, H. M., Abawi, G. S., Wolfe, D. W., Schindelbeck, R. R., Moebius-Clune, B. N., & Gugino, B. K. (2009). Use of an integrative soil health test for evaluation of soil management impacts. *Renewable Agriculture and Food Systems*, *24*(3), 214-224. https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/abs/use-of-an-integrative-soil-health-test-for-evaluation-of-soil-management-impacts/D7D791B872A8B69750ADE3669F1B9546

Soil Health Scenario #4c: Fertility practices in organic vegetable systems

Scenario description	
Title of scenario	Fertility practices in organic vegetable systems
Source of information	Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., & Haering, K. (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. *Agriculture, ecosystems & environment*, *127*(1-2), 50-58.
Location and soil type	The study was established at Virginia Tech's Northern Piedmont Agricultural Research and Education Center (NPAREC) in Orange, Virginia on a Fauquier silty clay loam soil with a slope of 7–10%.
Land use and management history	The land was previously used for research and education trials.
Detailed description of management/treatments and study design	Replicated plots of eight treatments evaluated the agronomic and environmental effects of various fertilizer and compost additions in organic vegetable systems. Treatments described in the experiment included: • CTL, Control (no amendments) • F, Fertilizer (soil test laboratory recommended rates of inorganic N, P, and K fertilizers, applied annually) • LC, Low compost (20% of the agronomic N compost rate applied annually • LCF, Low compost + fertilizer (20% of the agronomic N compost rate plus supplemental fertilizer required to meet crop N needs, applied annually) • AC, High compost (agronomic N compost rate, applied annually) • BC, High compost (agronomic N compost rate, applied biennially, i.e., in years 1 and 3) • BCF, High compost + fertilizer (Agronomic N compost rate applied biennially, i.e., years 1 and 3, plus supplemental fertilizer required to meet crop N needs) • PL, Poultry litter (agronomic N poultry litter rate, applied annually) Amendments were analyzed and then applied at rates to meet either all crop N needs or 20% of crop needs. Chemical analyses and rates are detailed in the publication. Amendments were hand-applied during seedbed preparation, and incorporated within 24 hours with a rototiller. The plots were cropped over three seasons with pumpkins in 2000, then corn in 2001, and then bell pepper in 2002. Winter rye was planted as a cover crop, and weeds were controlled using rototilling to 10cm and mulching with barley straw. The mulch straw was analyzed and estimated to add 14,882 kg C /ha, 161 kg N /ha, and 85 kg P /ha, as it was incorporated along with the rye in the spring. Potassium bicarbonate was used to control fungal disease in the pumpkins. Mineral oil was applied to corn tips, and parasitic wasps were released in 2001 to control pests. Trickle irrigation was used when necessary to prevent crop failure. Composite soil samples were collected each fall to assess soil chemical properties. An on-farm soil quality test kit was used to evaluate bulk density, porosity and soil moisture. Lysimeters were installed to evaluate N losses in subsurface runoff from the CLT, AC, PL and F treatment plots. A rainfall simulation and runoff collection event was run on the same treatments to evaluate runoff water quality and quantity.
Time period of data collection	2000-2002

Measured soil health outcomes	
Summary of influence on soil health	The high compost rate treatments (AC, BC, BCF) increased soil carbon and decreased bulk density. High compost treatments also significantly reduced runoff, increase water holding capacity and demonstrated reduced nutrient loading.
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	The high compost rate treatments (AC, BC, BCF) increased soil carbon above the other treatments. Soil carbon content did not differ significantly between low compost rate treatment and the controls (CTL and F).
Bulk density	High compost rate treatments reduced bulk density notably within two seasons (AC, BC, BCF) when compared to the control and fertilizer treatment (CTL and F). Low compost rate applications decreased bulk density noticeably after 3 years.
Aggregate stability	Not measured.
N_2O & CO_2 emissions	Not measured. NRCS Comet Planner estimates increased nitrous oxide emissions from manure and compost amendments. However, considering, N_2O emissions, CO_2 emissions and carbon sequestration together, these practices are generally net carbon sinks.
Soil biodiversity	Not measured.
Additional Information	
Other data (yield, etc.)	High compost treatments increased water holding capacity after 3 years. Pumpkin and bell pepper yields were unaffected. Corn yields were higher in LCF, AC, BCF, PL and F than in the control, low compost and biennial compost treatments. Nitrate leachate analysis indicates that annual application of fertilizer at rates designed to provide plant available N will not impair groundwater quality, and have a similar impact as unamended treatments. Nutrient management planning can prevent subsurface N losses. Compost amended soil (AC) demonstrated an improved ability to absorb water, with some treatments allowing significantly more water to percolate into and be held by soil, and delayed commencement of runoff, due to decreased bulk density. Particulate concentrations (TSS) in runoff were higher in the control and fertilizer treatments. Compost-amended soil contributed the lowest amounts of all combined forms of N to runoff load due to reduced runoff volume. The compost amended soil had the highest concentrations of dissolved phosphorus (DRP) and total phosphorus (TP), but had lowest total P loading due to high rates on infiltration and low runoff volumes. “An increase in the risk of nutrient transport to surface water due to an increase of C, N and P concentrations in runoff water from compost-amended soils be balanced by increased infiltration, porosity, and water-holding capacity that reduce runoff volume“ (Evanylo et al., 2008). By the end of the experiment, soil P increased by 52 ppm in the high compost AC and BCF treatments. All treatments increased in soil test P at the 0.001 probability level, in the following order: CTL < LC <F<PL< LCF < BC < AC< BCF. The authors offer some warning against long term compost soil amendments; “Such a high soil P accumulation rate under continuous compost addition may result in increased risk of P transport from soil to surface water” (Evanylo et al., 2008).

Data limitations	Replicated plot research is capable of detecting the significant impacts of management on soil health outcomes. Due to the time period of the study, long term impacts of these practices were not evaluated. Subsurface phosphorus flux was not measured.
References	Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., & Haering, K. (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. *Agriculture, ecosystems & environment*, *127*(1-2), 50-58.

Soil Health Scenario #5a: Hayland with broadcast manure compared to incorporation with aerator

Scenario description	
Title of scenario	Hayland with broadcast manure compared to manure incorporation with aerator
Source of information	Long-term on-farm research in Vermont, results of which have been published in two articles: White, A., Faulkner, J. W., Conner, D., Barbieri, L., Adair, E. C., Niles, M. T., Mendez, V.E. & Twombly, C. R. (2021). Measuring the Supply of Ecosystem Services from Alternative Soil and Nutrient Management Practices: A Transdisciplinary, Field-Scale Approach. *Sustainability*, *13*(18), 10303. Twombly, C. R., Faulkner, J. W., & Hurley, S. E. (2021). The effects of soil aeration prior to dairy manure application on edge-of-field hydrology and nutrient fluxes in cold climate hayland agroecosystems. *Journal of Soil and Water Conservation*, *76*(1), 1-13.
Location and soil type	A farm in Shelburne, Vermont Vergennes clay, Covington silty clay, and Palatine silt loam at 3% and 2.7% slope
Land use and management history	Fields were in hay production for at least 10 years prior to the research study being set up.
Detailed description of management/treatments and study design	A field-scale paired watershed study was set up to evaluate the effects of using an aerator prior to manure application on mixed legume-grass hay fields in Vermont. Two fields with similar characteristics were chosen to be control and treatment fields and edge-of-field water quality monitoring stations were installed. From 2012-2014 the two fields were managed the same way to evaluate inherent differences in hydrologic characteristics among the two fields. Beginning in June 2014, a 4.42-meter-wide vertical-tine aerator was used before manure application in the treatment field. Water quality parameters were monitored through the duration of the study. Soil health was measured using the CASH test at the beginning and end of the study, in 2012 and 2018. Greenhouse gas emissions were monitored in years 2016-2018. Yield and economic data were also tracked through the duration of the study.
Time period of data collection	2012-2018

Measured soil health outcomes	
Summary of influence on soil health	Overall CASH soil health scores increased in both fields, but to a greater extent in the aerated field. Organic matter, aggregate stability and respiration increased in both fields, more so in the control field.
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	Organic matter increased in both fields, by 1.6 percentage points in the aerated field, and 2 percentage points in the control field.
Bulk density	Not measured.

Aggregate stability	Aggregate stability increased in both fields, by an additional 17.4 percentage points in the control field and by an additional 25.8 percentage points in the aerated field.
N_2O & CO_2 emissions	Overall, N_2O was greater in the aerated field, and both fields were net carbon sinks. Average N_2O flux in the aerated field was 753 mg N_2O/m^2/year, equivalent to 2.24 MT CO_2e /hectare/year. In the control field flux was 596 mg N_2O/m^2/year, and 1.77 MT CO_2e /hectare/year. Average CO_2 flux in the aerated field was 663355 mg CO_2/m^2/year, equivalent to 6.63 MT CO_2e /hectare/year. In the control field flux was 692748 mg $C0_2/m^2$/year, and 6.98 MT CO_2e /hectare/year. Considering, N_2O emissions, CO_2 emissions and carbon sequestration together, both fields were net carbon sinks and the control field was a larger sink.
Soil biodiversity	Soil biodiversity was not measured. Respiration increased by 0.3 mg CO_2 in the aerated field and by 0.4 mg CO_2 in the control field. Active carbon increased by 68 ppm in the aerated field and by 40 ppm in the control field.
Additional Information	
Other data (yield, etc.)	No discernable trend in yields between the two fields was observed. The aerated field grossed $36 less than the control field. Aeration reduced concentrations of dissolved nutrient and suspended solids, but increased total runoff volumes, and thus had no significant impact on nutrient loads.
Data limitations	Data only shows comparison between two fields with clay soils over time, so should not be assumed to be representative of all fields.
References	White, A., Faulkner, J. W., Conner, D., Barbieri, L., Adair, E. C., Niles, M. T., Mendez, V.E. & Twombly, C. R. (2021). Measuring the Supply of Ecosystem Services from Alternative Soil and Nutrient Management Practices: A Transdisciplinary, Field-Scale Approach. *Sustainability*, *13*(18), 10303. Twombly, C. R., Faulkner, J. W., & Hurley, S. E. (2021). The effects of soil aeration prior to dairy manure application on edge-of-field hydrology and nutrient fluxes in cold climate hayland agroecosystems. *Journal of Soil and Water Conservation*, *76*(1), 1-13.

Soil Health Scenario #5b: Hayland with injected manure, with and without urease inhibitor

Scenario description	
Title of scenario	Hayland with different nitrogen sources (manure and synthetic urea) and application methods (manure injection and surface application)
Source of information	Brickman, S., Adair, E.C., Darby, H. (& maybe other coauthors). (Manuscript in preparation). Drivers of soil-borne greenhouse gas emissions from different nitrogen sources and manure application methods in a Northeast hayfield.
Location and soil type	Borderview Research Farm in Alburgh, VT . Soils were a mix of poorly drained Covington silty clay loam and well drained Nellis silt loam (Soil Survey Staff, 2017) with a texture class of silt loam.
Land use and management history	The experiment was conducted in a hayfield that had been unfertilized since 2006 and contained a mix of grasses (*Phalaris arundinacea, Poa pratensis, Frestuca pratensis, Agrostis stolonifera, Doctylis glomerata*), legumes (*Trifolium* sp.), and weeds (*Taraxacum officinale*).
Detailed description of management/treatments and study design	The trial occurred over two growing seasons from June 2020-November 2021, and treatments were arranged in a randomized complete block arrangement. Within each block, the plot treatments were the application of a commercial urease inhibitor, ContaiN MAX (AgXplore, Parma, MO), and control (no application of the inhibitor). Each plot was divided into four subplots with treatments of manure injection, surface manure application, synthetic fertilizer amendment, and control (no fertilization). We applied fertilizer and inhibitor treatments within a week after harvests in 2020 and 2021. Treatment application dates were 16 June 2020, 13 August 2020, 2 June 2021, and 30 July 2021. Liquid dairy cattle manure was applied at a rate of 42,092.7 L ha^{-1} using a tractor-drawn tank spreader (Kuhn) in the broadcast plots and a shallow-slot manure injector (Veenhuis Euroject 1200 grassland injector) in the injection plots. The injector disk cut slots 2.5-5 cm deep with 20 cm between each strip, and the shoe following the disk placed manure in the slot so that the manure extended from the slot bottom to the soil surface in strips that ran the length of each injection subplot. For the manure with inhibitor treatments, ContaiN MAX was mixed with the manure before application to achieve a target rate of 1.3 L ha^{-1}. We applied urea with and without inhibitor at a rate of 145.7 kg ha^{-1} using a variable rate drop spreader. Control without inhibitor subplots were watered without any fertilizer application, and control with inhibitor subplots were sprayed with ContaiN MAX (without fertilizer application). We harvested all subplots three times both years, but in 2020, yield and forage quality were only measured during the latter two harvests. Harvest occurred during mid to late boot stage for the first cut and was targeted for when the forages reached a height of 25-30 cm (10-12 inches) for subsequent cuts.
Time period of data collection	2 years, June 2020 – November 2021
Measured soil health outcomes	
Summary of influence on soil health	We did not find nitrogen source (manure or synthetic urea), manure application method (injection or broadcast), or inhibitor application to be important predictors of N_2O and CO_2 fluxes. Average daily N_2O emissions were generally low in our trial compared to those measured in manure injection and broadcast trials in annual

	corn systems (Dittmer et al., 2020; Duncan et al., 2017) but comparable to those measured in perennial forage systems (Rodhe et al., 2006; Sadeghpour et al., 2018). Because the trial was just two years, we did not expect to observe changes in soil carbon in response to treatment, and we only measured total carbon, total nitrogen, soil organic matter, and bulk density in control without inhibitor subplots.
Directionality and measured extent of impact on selected soil health indicators:	
Organic matter	Mean 8.7% organic matter at the study site
Bulk density	Mean 1.22 g cm^{-3} at the study site
Aggregate stability	Not measured
N_2O & CO_2 emissions	Rather than manure application method or nitrogen source, the primary drivers of N_2O and CO_2 emissions were related to environmental conditions – soil moisture or temperature – and nitrogen availability. Because the inhibitor did not measurably impact emissions, we describe treatment differences by fertilizer type and manure application method. Across all treatments, the mean daily flux rate for N_2O and CO_2 was 21.4 ± 49.3 g N_2O-N ha^{-1} d^{-1} and 45.7 ± 24.7 kg CO_2-C ha^{-1} d^{-1}, respectively. Daily N_2O fluxes ranged from 0-670.8 g N_2O-N ha^{-1} d^{-1} and CO_2 fluxes ranged from 0-164.5 kg CO_2-C ha^{-1} d^{-1}. The most important predictors of daily N_2O fluxes were soil moisture, CO_2 emissions, and NO_3-N concentration, with higher values of these variables predicting higher N_2O fluxes. The mean daily N_2O fluxes for manure injection, manure broadcast, synthetic fertilizer, and the control were 28.8 ± 52.0 g N_2O-N ha^{-1} d^{-1}, 30.8 ± 70.9 g N_2O-N ha^{-1} d^{-1}, 15.3 ± 33.3 g N_2O-N ha^{-1} d^{-1}, and 10.3 ± 22.3 g N_2O-N ha^{-1} d^{-1}, respectively. Similar to N_2O daily fluxes, abiotic variables drove CO_2 fluxes, but unlike for N_2O fluxes, soil temperature was the most important predictor, followed by days since treatment application, NH_4-N concentration, N_2O fluxes, and soil moisture. Daily CO_2 fluxes increased with temperature, with the lowest fluxes occurring at cooler soil temperatures in Oct-Nov and the highest in May-Sept, when soil temperatures averaged 8.9 ± 4.7 ºC and 18.6 ± 2.7 ºC, respectively. The mean daily CO_2 fluxes for manure injection, manure broadcast, synthetic fertilizer, and the control were 51.1 ± 28.7 kg CO_2-C ha^{-1} d^{-1}, 46.3 ± 26.4 kg CO_2-C ha^{-1} d^{-1}, 41.4 ± 21.4 kg CO_2-C ha^{-1} d^{-1}, and 44.2 ± 20.5 kg CO_2-C ha^{-1} d^{-1}, respectively.
Soil biodiversity	Not measured
Additional Information	
Other data (yield, etc.)	In both years, yields at each harvest after treatment application were higher for the manure and synthetic fertilizer treatments than the control but were similar across fertilizer type, inhibitor use, and manure application method. The manure treatments had similar mean yields to the synthetic fertilizer treatment in both years, although the maximum values for manure treatments were 1.6 times higher than those for synthetic fertilizer, suggesting that manure application can generate larger yields but is mostly comparable to synthetic fertilizer. When yields were measured in May 2021, before treatment application, both manure treatments had mean yields 1.6-2 times larger than those of synthetic fertilizer and the control, suggesting that while manure amendment mostly did not have an impact on yields within 5-7 weeks after application, it may have long-term effects on biomass production.

Data limitations	Soil moisture levels were low throughout much of the growing season during our trial, so treatment effects may be more pronounced and GHG fluxes may be higher in wetter conditions.
References	Dittmer, K. M., Darby, H. M., Goeschel, T. R., & Adair, E. C. (2020). Benefits and tradeoffs of reduced tillage and manure application methods in a Zea mays silage system. *Journal of Environmental Quality, 49*(5), 1236-1250. https://doi.org/https://doi.org/10.1002/jeq2.20125 Duncan, E. W., Dell, C. J., Kleinman, P. J. A., & Beegle, D. B. (2017). Nitrous Oxide and Ammonia Emissions from Injected and Broadcast-Applied Dairy Slurry. *Journal of Environmental Quality, 46*(1), 36-44. https://doi.org/10.2134/jeq2016.05.0171 Rodhe, L., Pell, M., & Yamulki, S. (2006). Nitrous oxide, methane and ammonia emissions following slurry spreading on grassland. *Soil Use and Management, 22*(3), 229-237. https://doi.org/10.1111/j.1475-2743.2006.00043.x Sadeghpour, A., Ketterings, Q. M., Vermeylen, F., Godwin, G. S., & Czymmek, K. J. (2018). Nitrous Oxide Emissions from Surface versus Injected Manure in Perennial Hay Crops. *Soil Science Society of America Journal, 82*(1), 156-166. https://doi.org/https://doi.org/10.2136/sssaj2017.06.0208

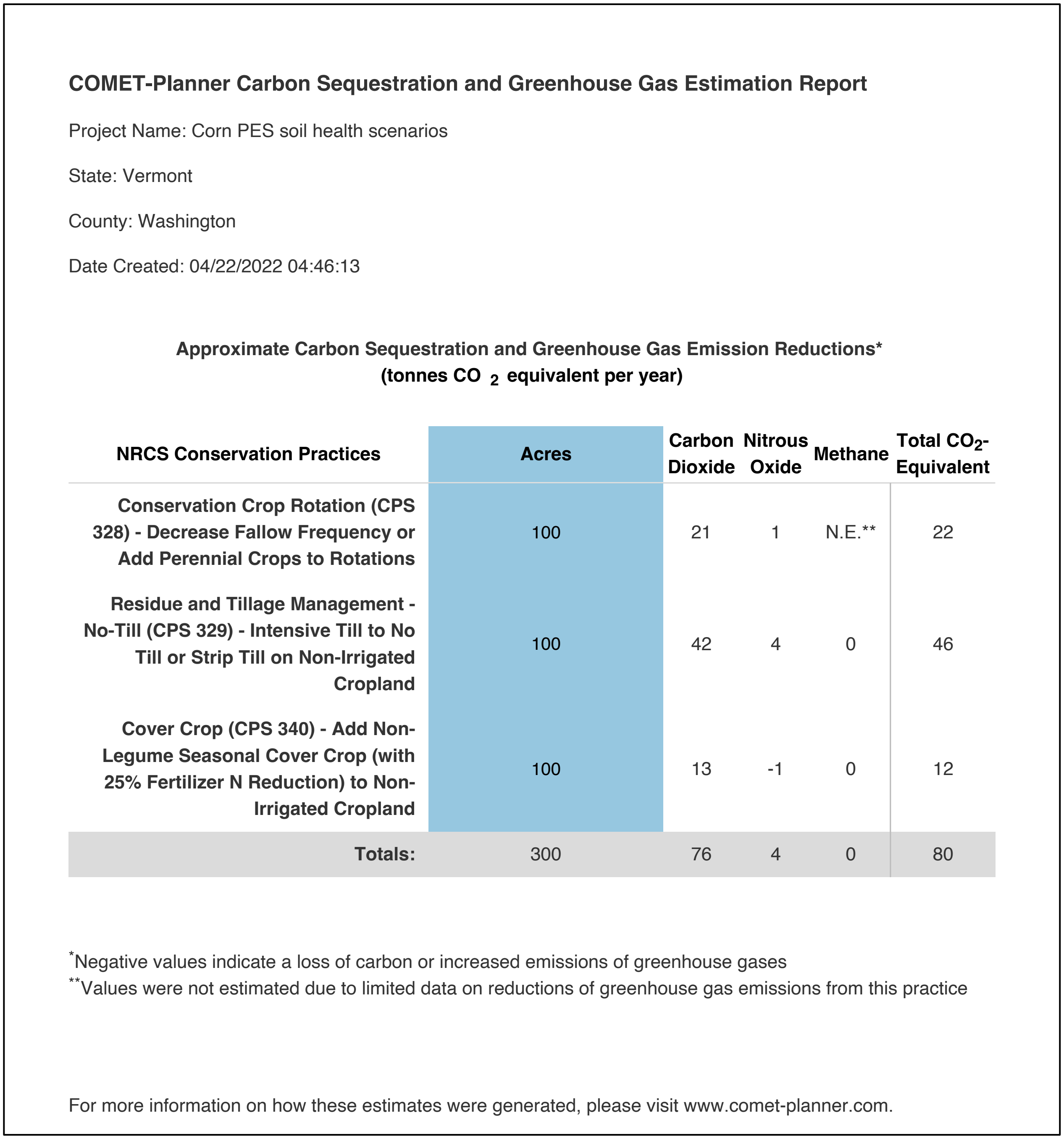
Table 1. Summary table of management scenarios and measured influence on soil health indicators. Red indicates negative outcomes, green indicates positive outcomes. Scenarios are intended to be illustrative and many have limited inference across other farms and fields.

Title of scenario	**Best Management Practice Corn (No-till and Cover Crop)**	**Corn hay rotation**	**Transition from annual cropping to rotational grazing**	**Restoring soil function with management-intensive grazing rotation**
Scenario number	1	2	3a	3b
Soil texture	Rocky silt loam	Silt loam	Clay loam	Clay & silty clay
Time period	3 years, 2017-2020	11 years, 2012 – 2021	2 years, 2017-2018	6 years, 2015 - 2021
Influence on organic matter (indicator of Climate regulation, Downstream flood risk mitigation, & Climate resilience)	Over three years the accumulated effects were a net increase of 0.3% organic matter more in the BMP treatment than the conventional treatment.	Corn-hay rotation had a net additional 0.25% to 1.22 % organic matter compared to continuous corn treatment.	No change in soil organic carbon was detected between years	Preliminary data shows an increase of soil organic matter across the farm.
Influence on bulk density (indicator of Climate regulation & Downstream flood risk mitigation)	Bulk density was not measured, but penetrometer data is used as a proxy. Penetrometer data in 2020 was not statistically significantly different among the treatments.	No significant difference observed between treatments for bulk density samples collected in 2021.	Bulk density increased between 2017-2018.	Not reported.
Influence on aggregate stability (Indicator of Downstream flood risk mitigation, Soil conservation & Climate resilience)	Over three years the accumulated effects were a net increase of 11.1% more in water stable aggregates in the BMP treatment than the conventional treatment.	Corn-hay rotation had a net additional 9.4% to 41.3 % aggregate stability compared to continuous corn treatment (significant to p=0.1).	No change in water stable aggregates between years	Not reported.
Influence on N2O & CO2 emissions (indicator of Climate regulation)	Not measured. NRCS Comet Planner estimates non-legume cover crops increase N2O emissions and no-till reduces N2O emissions. Considering emissions & sequestration together, Comet Planner estimates the combination of practices is a net carbon sink.	Not measured. However, NRCS Comet Planner estimates adding perennial crop rotation reduce nitrous oxide emissions.	Not measured. However, NRCS Comet Planner estimates the conversion to forage and biomass plantings would reduce nitrous oxide emissions.	Not measured. Not enough information exists to project the impact of rotational grazing on nitrous oxide emissions.
Influence on soil biodiversity (indicator of Biodiversity)	No measure of biodiversity was collected. However, indicators of biological activity were collected. Over three years there was a greater net increase in soil respiration in the BMP treatment than in the conventional treatment.	No measure of biodiversity was collected. However, indicators of biological activity were collected. Corn-hay rotation had an additional 0.489 to 0.623 CO2 g soil-1 respiration compared to continuous corn treatment (significant to p=0.1).	Increases in soil biological activity (β-glucosidase activity, microbial biomass carbon and potentially mineralizable N) were observed.	Not reported.

Table 2 continued. Summary table of management scenarios and measured influence on soil health indicators. Red indicates negative outcomes, green indicates positive outcomes. Scenarios are intended to be illustrative and many have limited inference across other farms and fields.

Title of scenario	**Vegetables with a cover crop rotation**	**Vegetable production with reduced tillage**	**Fertility practices in organic vegetable systems**	**Hayland with aerataor**	**Hayland with variable nitrogen sources, manure applications & inhibitor use**
Scenario number	4a	4b	4c	5a	5b
Soil texture	Silt loam	Silt loam	Silty clay loam	Clay	Silt loam
Time period	4 years, 2003 - 2007	4 years, 2003 - 2007	2 years, 2000-2002	6 years, 2012-2018	2 years, 2020 - 2021
Influence on organic matter (indicator of Climate regulation, Downstream flood risk mitigation, & Climate resilience)	At the end of the study organic matter content was higher by 0.2% in the soil building rotation.	No significant differences in organic matter were detected in this study.	High compost rate treatments increased organic carbon more than other treatments. Organic carbon did not differ significantly between low compost rate treatment and the controls.	Organic matter increased in both fields, but more so in the control field.	Not measured.
Influence on bulk density (indicator of Climate regulation & Downstream flood risk mitigation)	Bulk density was not measured, but penetrometer data is used as a proxy. Surface and subsurface hardness were higher in the soil building rotation than the continuous cropping plots at the end of the experiment.	Bulk density was not measured. Surface hardness was significantly higher in the no till than the other two tillage treatments in the soil building rotation ($p<.01$), and significantly higher in zone till than full till in the continuous rotation.	High compost rate treatments reduced bulk density notably within two seasons. Low compost rate applications decreased bulk density noticeably after 3 years.	Not measured.	Not measured.
Influence on aggregate stability (Indicator of Downstream flood risk mitigation, Soil conservation & Climate resilience)	At the end of the experiment, aggregate stability was 5.1% higher in the soil building treatment than in the continuous cropping treatment	Aggregate stability was significantly higher in the zone tillage treatment in continuous rotation. The no till treatment was significantly higher in the soil building rotation ($p<0.05$).	Not measured.	Aggregate stability increased in both fields, but more so in the control field.	Not measured.
Influence on N_2O & CO_2 emissions (indicator of Climate regulation)	Not measured. NRCS Comet Planner tool estimates that perennial crop rotations reduce nitrous oxide emissions.	Not measured. NRCS Comet Planner tool estimates that reduced and no-till decrease nitrous oxide emissions.	Not measured. NRCS Comet Planner estimates increased N2O emissions from manure and compost amendments. Considering emissions sequestration together, these practices are generally net carbon sinks.	N2O flux was greater in the aerated field, though both fields were net carbon sinks. Considering emissions and sequestration together, both fields were net carbon sinks, the control field was a larger sink.	No significant influences on CO2 or N2O emissions from from nitrogen sources, manure application method or the use of urease inhibitor.
Influence on soil biodiversity (indicator of Biodiversity)	Soil biodiversity was not measured but active carbon can be used as an indication of biological activity. At the end of the experiment active carbon level were similar, but slightly higher in the soil building rotation.	No indicator of biological diversity was monitored. The best indicator of biological activity used in this study was active carbon. Active carbon was significantly reduced in the no till treatment only in the continuous rotation.	Not measured.	Soil biodiversity was not measured. Respiration increased by 0.3 mg CO2 in the aerated field and by 0.4 mg CO2 in the control field. Active carbon increased by 68 ppm in the aerated field and by 40 ppm in the control field.	Not measured.

Appendix A. Comet Planner output reports with scenario practices



COMET-Planner Carbon Sequestration and Greenhouse Gas Estimation Report

Project Name: Corn PES soil health scenarios

State: Vermont

County: Washington

Date Created: 04/22/2022 04:46:13

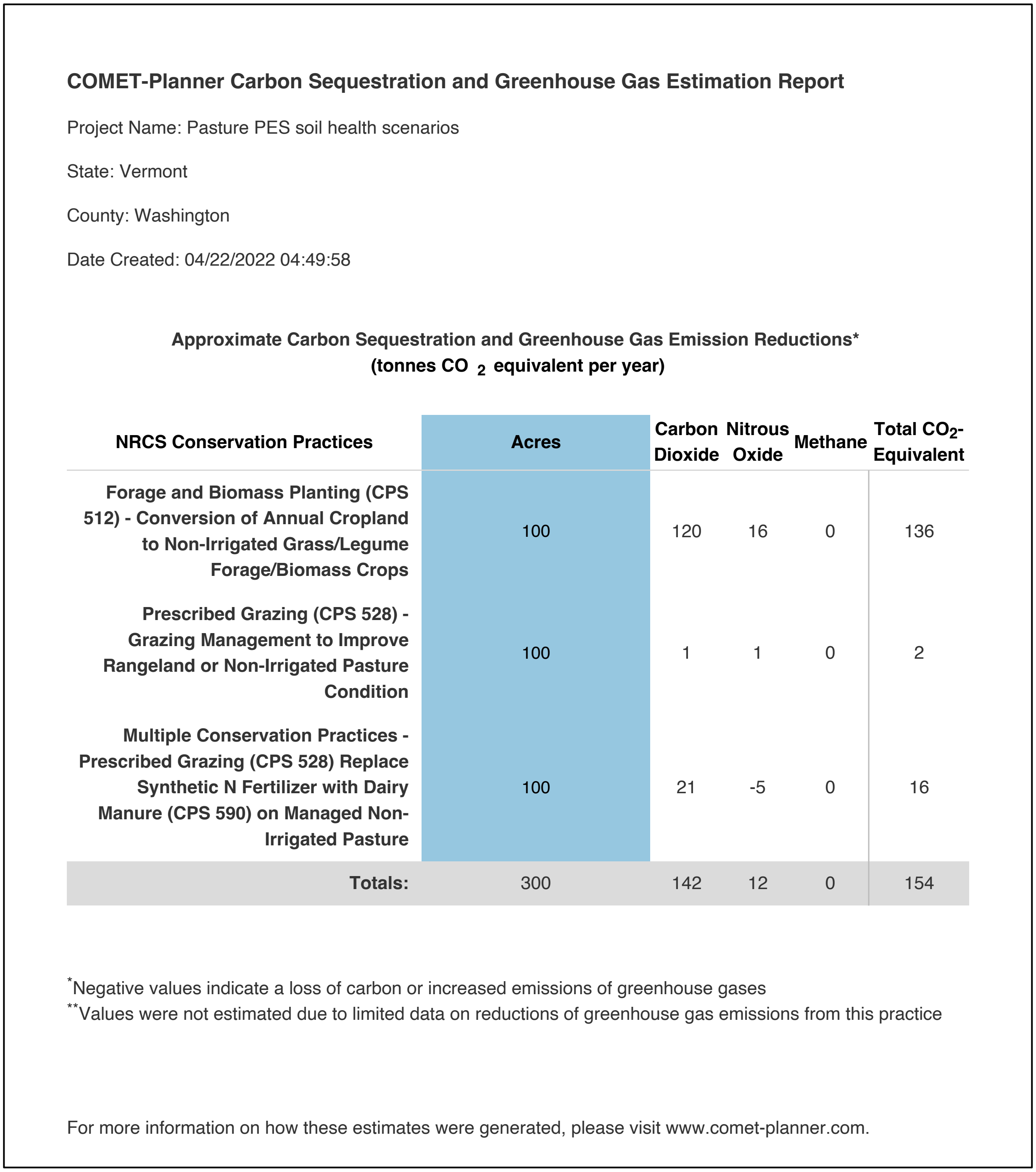
Approximate Carbon Sequestration and Greenhouse Gas Emission Reductions*
(tonnes CO_2 equivalent per year)

NRCS Conservation Practices	Acres	Carbon Dioxide	Nitrous Oxide	Methane	Total CO_2-Equivalent
Conservation Crop Rotation (CPS 328) - Decrease Fallow Frequency or Add Perennial Crops to Rotations	100	21	1	N.E.**	22
Residue and Tillage Management - No-Till (CPS 329) - Intensive Till to No Till or Strip Till on Non-Irrigated Cropland	100	42	4	0	46
Cover Crop (CPS 340) - Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to Non-Irrigated Cropland	100	13	-1	0	12
Totals:	300	76	4	0	80

*Negative values indicate a loss of carbon or increased emissions of greenhouse gases
**Values were not estimated due to limited data on reductions of greenhouse gas emissions from this practice

For more information on how these estimates were generated, please visit www.comet-planner.com.

Figure 2. NRCS Comet Planner report of practices in the corn soil health scenarios reviewed in this report. Generated at http://comet-planner.com.



COMET-Planner Carbon Sequestration and Greenhouse Gas Estimation Report

Project Name: Pasture PES soil health scenarios

State: Vermont

County: Washington

Date Created: 04/22/2022 04:49:58

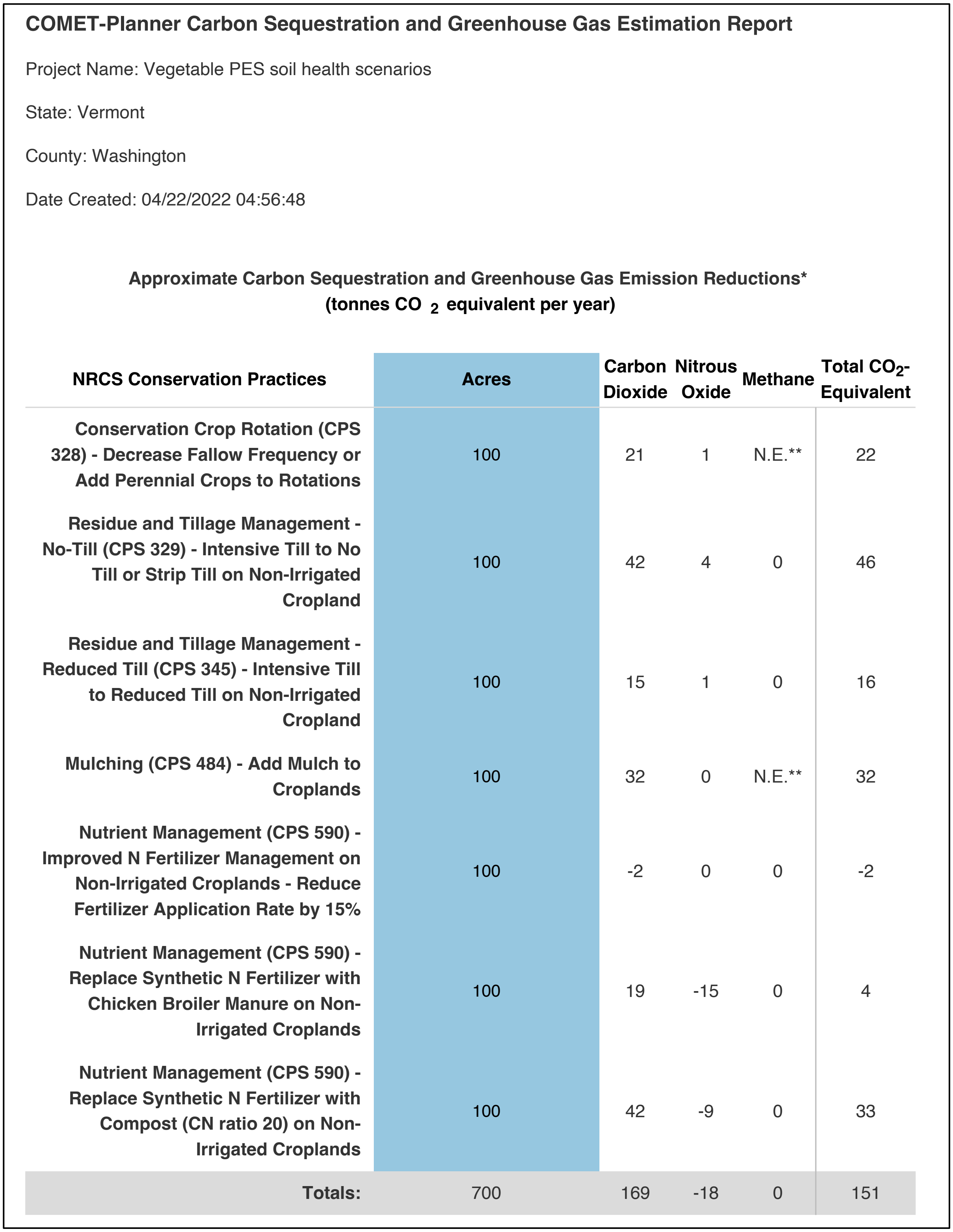
Approximate Carbon Sequestration and Greenhouse Gas Emission Reductions*
(tonnes CO_2 equivalent per year)

NRCS Conservation Practices	Acres	Carbon Dioxide	Nitrous Oxide	Methane	Total CO_2-Equivalent
Forage and Biomass Planting (CPS 512) - Conversion of Annual Cropland to Non-Irrigated Grass/Legume Forage/Biomass Crops	100	120	16	0	136
Prescribed Grazing (CPS 528) - Grazing Management to Improve Rangeland or Non-Irrigated Pasture Condition	100	1	1	0	2
Multiple Conservation Practices - Prescribed Grazing (CPS 528) Replace Synthetic N Fertilizer with Dairy Manure (CPS 590) on Managed Non-Irrigated Pasture	100	21	-5	0	16
Totals:	300	142	12	0	154

*Negative values indicate a loss of carbon or increased emissions of greenhouse gases
**Values were not estimated due to limited data on reductions of greenhouse gas emissions from this practice

For more information on how these estimates were generated, please visit www.comet-planner.com.

Figure 3. NRCS Comet Planner report of practices in the pasture soil health scenarios reviewed in this report. Generated at http://comet-planner.com.



COMET-Planner Carbon Sequestration and Greenhouse Gas Estimation Report

Project Name: Vegetable PES soil health scenarios

State: Vermont

County: Washington

Date Created: 04/22/2022 04:56:48

Approximate Carbon Sequestration and Greenhouse Gas Emission Reductions*
(tonnes CO_2 equivalent per year)

NRCS Conservation Practices	Acres	Carbon Dioxide	Nitrous Oxide	Methane	Total CO_2-Equivalent
Conservation Crop Rotation (CPS 328) - Decrease Fallow Frequency or Add Perennial Crops to Rotations	100	21	1	N.E.**	22
Residue and Tillage Management - No-Till (CPS 329) - Intensive Till to No Till or Strip Till on Non-Irrigated Cropland	100	42	4	0	46
Residue and Tillage Management - Reduced Till (CPS 345) - Intensive Till to Reduced Till on Non-Irrigated Cropland	100	15	1	0	16
Mulching (CPS 484) - Add Mulch to Croplands	100	32	0	N.E.**	32
Nutrient Management (CPS 590) - Improved N Fertilizer Management on Non-Irrigated Croplands - Reduce Fertilizer Application Rate by 15%	100	-2	0	0	-2
Nutrient Management (CPS 590) - Replace Synthetic N Fertilizer with Chicken Broiler Manure on Non-Irrigated Croplands	100	19	-15	0	4
Nutrient Management (CPS 590) - Replace Synthetic N Fertilizer with Compost (CN ratio 20) on Non-Irrigated Croplands	100	42	-9	0	33
Totals:	700	169	-18	0	151

Figure 4. NRCS Comet Planner report of practices in the vegetable soil health scenarios reviewed in this report. Generated at http://comet-planner.com.

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