Harnessing long-term data to understand the N demands of soil C sequestration across a crop diversification gradient

Introduction

Soils are the largest terrestrial pool of the global carbon (C) cycle [1] and limiting global warming to 1.5°C will not be achieved without sustainable soil management in agroecosystems [3,4]. The importance of soil C sequestration gained renewed attention with the 4 per mille initiative signed by more than 100 nations at the 21st COP in Paris, which emphasizes that increasing global soil C stocks by 0.4% per year could mitigate the annual increase in atmospheric CO_2. However, the potential to restore soil organic C (SOC) varies at smaller scales with climate, soil type, land use history, and management practices. Some regions have larger potential for soil C storage due to a history of intensive production, which has depleted background stocks of soil organic matter (SOM). In the Midwestern U.S., a region which represents 75% of all corn production in the nation [5], 50% of original soil C has been lost [6]. In addition, the simplified commodity production systems in the region depend on substantial use of fossil energy through fertilizers and fuel for field operations leading to widespread environmental consequences. These include greenhouse gas (GHG) emissions from direct and indirect sources that contribute to climate change [7], N leaching losses that cause hypoxia in the Gulf of Mexico [8], biodiversity loss [9], and soil erosion [5]. At the same time, a growing body of evidence highlights that restoring crop diversity can reduce external input use and associated emissions [10], and increase SOC [11,12], nutrient retention [2,13,14], and improve yield stability and resilience to climate change [15-17]. Diversifying Midwestern agroecosystems thus has vast potential to return C to soil while mitigating a wider suite of environmental crises.

Stable SOM fractions have a typical C:N ratio of 10-12. Thus, realizing the 1200 Tg annual increase in soil C proposed by 4 per mille, for instance, would require an estimated 100-200 Tg N per year [18]. Further, if these N requirements are met through inorganic fertilizer additions, this may negate potential ecosystem benefits because of the embodied emissions in fertilizer production and the likelihood of exacerbating N leaching and N_2O emissions [7]. Yet, current debates around the N needs of soil C accrual are often framed too narrowly, missing key insights from ecological science, including nuances related to N source (e.g., legume cover crops, fertilizer, manure) and the broader ecosystem context of N management, such as cropping system diversity. Functioning C markets and other incentives intended to support sustainable agriculture depend on a robust understanding of these ecosystem dynamics. We propose to compile and analyze data from multiple long-term experiments testing management systems that span a diversification gradient in the Midwestern U.S. Specifically, this research will advance understanding of coupled C and N dynamics relevant to best practices for both soil C sequestration and N retention, while building a valuable database for further refinement to inform effective policy designs for sustainable agriculture.

Background

Agricultural systems provide a unique opportunity to identify generalizable principles of SOC dynamics in terrestrial ecosystems while simultaneously identifying management practices for increased sustainability. Agroecosystems can have highly degraded SOC stocks, and C and N inputs at long-term experimental sites can vary by an order of magnitude due to management practices, such as crop rotation diversity, soil disturbance, and fertilization. In the proposed research, we will link insights from scholarship on diversified farming systems and ecological nutrient management to quantify and understand the N requirements of soil C sequestration across a management gradient.

Diversified farming systems

Diversified farming systems are defined by intentional management using practices such as varietal diversity, cover crops, and native habitat retention to increase the diversity of crops, livestock, and non-agricultural biodiversity from field to landscape scales [19]. The benefits of diversified farming systems for multiple ecosystem services are supported by fundamental principles from research on biodiversity and ecosystem functioning [20,21], as well as experiments and observational studies in agricultural systems [22,23], and regional or national-level trends [24]. Agricultural diversity is a continuum, influenced by several interacting dimensions of management systems—most obviously, the use of planned crop and livestock diversity (and associated diversity, such as pollinators, soil microorganisms, etc.) across scales [19]. Other key dimensions that influence agricultural diversity are the frequency and intensity of soil disturbance through tillage or other mechanical operations, and the source and rate of external inputs such as fertilizers [25]. Our analysis will integrate these three core dimensions of cropping system diversification to understand interactions between N inputs and SOC.

Because agroecosystems typically have lower biodiversity than natural ecosystems, small increases in crop *functional diversity* (i.e., the diversity of crop functional traits) can lead to large benefits for ecosystem functions [26,27]. Strategies for adding functional diversity to grain farms in the Midwest include cultivation of perennial forages, legume N sources, and non-harvested winter cover crops, all of which have traits linked to root and shoot C inputs to soil [12]. Legume N fixation is a plant trait that supplies N in organic forms that are less susceptible to environmental losses compared to synthetic N fertilizers [2,10,28,29]. Grass cover crops have traits that are effective for immobilizing excess N in agroecosystems [30-32]. Functional traits also determine how C inputs are distributed throughout the soil profile. Annual grain crops invest about five to seven times as much net primary productivity (NPP) in shoots compared to roots [33], whereas perennial forages invest approximately equivalent NPP in shoots and roots. Overall, diversifying rotations with perennials and cover crops increases the period of NPP and supplies more diverse root and plant residue inputs to soil, which can increase microbial diversity or activity and associated processes that stabilize both C and N in soil [34-36].

Ecological nutrient management to recouple C and N cycling dynamics

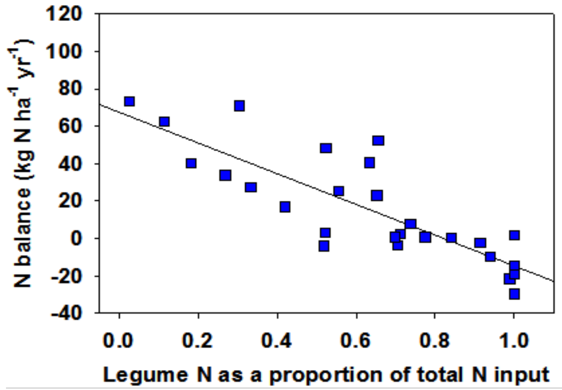
The production and application of synthetic N fertilizers represent the greatest use of fossil energy in agriculture, contributing substantially to its global warming potential [7]. Nitrogen is also one of the most challenging nutrients to manage because microbial processes quickly transform N among multiple chemical forms, driving multiple loss pathways [37]. Allowing fields to remain fallow for large portions of the year depletes SOM and increases NO_3^- leaching and N_2O emissions. In response to these challenges, ecological N management draws from ecosystem ecology to identify practices that sustain production while enhancing co-flows and retention of C, N, and other nutrients [2,38]. Practices that increase plant and microbial sinks for inorganic N in fields improve N retention [2,34,38]. That is, increasing SOC by diversifying crop rotations with cover crops or perennial species, and use of organic N sources such as manure, compost, and legumes [12,39], couples C and N cycles and enhances ecological processes that can conserve N in soil. Overall goals of ecological N management are to minimize the size of inorganic N pools that are most vulnerable to loss, while maximizing the capacity for the agroecosystem to use soluble N; for instance, by increasing crop functional diversity to increase the occupancy of niches and the diversity of soil biota. Another key goal is balancing N inputs with harvested exports over the long term.

N Balance: An environmental performance indicator

A robust indicator of potential N pollution is mass balance, calculated as the sum of N inputs minus harvested N outputs for a bounded system, such as a field or farm [2,40]. Such “partial” balances focus on the largest N flows managed by farmers rather than specific transformations or loss pathways. A mass balance is an integrated, ecosystem-based indicator of potential N losses in the case of surpluses, or mining of soil fertility in the case of deficits [41]. Sustained N surpluses – where N inputs are consistently greater than harvested exports – correlate with N losses [38,40,42]. There is now wide support for evaluating agricultural practices with this relatively simple metric, which can be measured accurately at scale [42,43].

The proposed research will use partial N balances to understand how N retention varies with SOC accumulation in agroecosystems. In our previous work developing a partial N balance approach for farms in the U.S. Corn Belt, we found that legume N sources reduce surplus N (Figure 1). All organic inputs supply both C and N, but farms with biological N fixation as the primary N source may have more efficient N cycling. As soil N pools increase, legumes decrease rates of N fixation and increase use of soil N because of the energetic cost of supplying C to their bacterial symbionts [29,44]. In contrast, long-term application of animal manure to meet crop N needs often results in N surpluses and may not represent a net sequestration of atmospheric CO_2 [45]. Overwintering cover crops and forages also extend the timeframe for living roots to assimilate and temporarily immobilize soil N while increasing C inputs through photosynthesis [12,13].

Figure 1. *Annual N balance is inversely related to the proportion of N inputs from legume N fixation*. Field-scale N mass balances calculated as total N inputs – harvested N exports for diversified grain farms in four states in the U.S. Midwest for five-year crop rotations [2]. Results show that an ecological approach to soil N management that incorporates legume N sources reduces surplus N in agroecosystems. For this sample, the most common legume N source was alfalfa grown for forage.



Project Approach

***Question 1:* Across long-term sites and management regimes, what is the rate of SOC accumulation per unit total N and C input? Is this relationship moderated by cropping system diversification?**

Hypotheses: We hypothesize that total SOC and the rate of SOC accumulation will increase with greater N and C inputs up to a maximum level, dependent on soil and climate conditions across sites. We predict that the total SOC stock per unit N input will increase along the diversification gradient (i.e., with increased crop functional diversity, use of organic N sources, and reduced soil disturbance).

Methods:

Site selection: We have confirmed access to datasets from 6 long-term experiments that have measured SOC over time: two at the KBS LTER in MI (MCSE and Resource Gradient), one in Wooster, OH (Triplett-Van Doren), and three through the USDA LTAR network: UMRB in Ames, IA; CMRB in MO; and ECB in OH (see attached letters of support). We also plan to include the publicly available data from the multi-state Sustainable Corn CAP, which is well curated and includes data on SOC, agronomic management, yield and crop biomass, GHG emissions, and water quality. We will spend the initial project period (1-2 months) identifying additional experiments to include (e.g., WICST in WI and the long-term N rate and crop rotation study at Iowa State). We will convert SOC data from all sites to the same units (i.e., concentration, or area basis using bulk density) and use the greatest sampling depth possible based on available data. While sampling depths differ by site, the change in SOC over time will reflect meaningful treatment differences within sites, even though deeper samples provide a more robust measure of changes in total SOC stocks.

The management systems at the sites currently confirmed span a range of: (1) crop rotation diversity, from continuous monoculture to 3-4 grain rotations with and without cover crops, to perennial successional plots; (2) no-till, reduced till, and conventional till; and (3) N inputs at more than ten rates, and from synthetic and leguminous sources.

Diversification gradient: We will construct an index of diversification that combines and normalizes three core components of the management systems at each site. First, we will calculate a continuous metric of functional diversity for all crops included in a complete rotation cycle (e.g., Rao's Q) [28]. Second, we will develop an index of soil disturbance (e.g., a scale of 1-4, from high to low tillage intensity). Third, we will include a simple index for N source (e.g., fertilizer = 1; manure =2; legume =3). Then we will aggregate these three indicators into a continuous "diversification" variable to test in hierarchical models (see below). This approach will provide more nuanced understanding of ecological mechanisms compared to broad treatment categories such as "conventional" and "organic" that encompass substantial variation in actual practices. However, we will also test the broad management categories designated at each site, along with individual management practices of interest (e.g., tillage type, N rate), which can be considered alone or in different combinations relevant to potential cost-share and C market programs.

Modeling approach: We will model SOC accumulation per unit total N added together with key covariates. Across sites, we expect steady state SOC levels where C inputs are approximately balanced by C losses, especially at sites in place for multiple decades. Typically, total SOC at steady state approaches a maximum level over time in an asymptotic relationship [46] based on accrual (inputs minus losses):

$$SOC = SOC_{max} * [t / (\alpha + t)]$$

where SOC is total SOC, SOC_{max} is the maximum SOC for a given site and management system, α is the rate of SOC accrual and t is the time. The specific best-fit functions may differ by site: we will use data on SOC over time from each site and management system to determine the best function and then estimate the parameters SOC_{max} and α, which will be the primary dependent variables in the models. We may be able to use dynamics in longer-term datasets to make inferences about these parameters in shorter-term datasets, especially for similar locations and soil types. Intercept parameters will be site specific, and for cross-site comparisons must be controlled using a random site factor and variables such as clay content and climate. Next, SOC_{max} and α (rate of SOC accrual) will be modelled using a hierarchical (mixed-effects) framework in R. Explanatory variables will include total N input, C inputs (NPP and manure if relevant), environmental factors, and the diversification index described above. A hierarchical modeling approach is useful for explaining variation in aggregated parameters such as this index because it allows for interpretation of deviations above or below an overall mean across sites. We expect that C and N inputs such as NPP and total N rate will likely have a greater influence on SOC_{max}, when controlling for environmental factors, while α will vary with factors such as tillage and crop functional diversity that influence the rate of SOC accrual.

We will follow the methods in Blesh and Drinkwater [2] to estimate N inputs from legume N fixation for cover crops, harvested legumes (e.g., soybeans), and forages combining information on yield or biomass and %N from each site with estimates of N derived from fixation from the literature (unless measured). We will follow the approach in King and Blesh [12] to quantify C inputs by treatment. We will use available data on crop yields on a dry matter basis together with allocation coefficients from the literature [33,47,48] to estimate C input from shoots, roots, and root exudates for each crop. We will account for any C inputs from manure, though our interpretation of results will consider that these may not represent net C sequestration at an ecosystem scale.

***Question 2*: How does agroecosystem N retention change with SOC accumulation? Does this relationship vary with different N sources (fertilizer, legume, manure)?**

Hypotheses: We hypothesize that agroecosystem N retention will increase with SOC across sites, but that this relationship will be mediated by climate, soil type, and the diversification index. We expect N retention to be highest with legume N sources, followed by manure, then fertilizer, and highest for rotations with cover crops and perennials, which have traits relevant to both SOC accrual and N retention.

Methods: We will use a hierarchical modeling approach as in Question 1 with N retention as the dependent variable. We will quantify N retention in two ways. First, for sites with long-term data on NO_3^- leaching and N_2O emissions, we will use these measures to estimate N losses, or do additional modeling as needed. For instance, at KBS, soil NO_3^- data are available, but estimating leaching on an area basis requires coupling these data with a hydrologic model such as SALUS to predict drainage [49]. We will follow methods in Syswerda, et al. [49], updating this analysis for the past decade. For all sites, we will use partial N balances (i.e., N surplus) as an indicator of N retention. We will follow the methods in Blesh and Drinkwater [2] and McLellan, et al. [42] to calculate N balances at the field/plot scale for the same period for which we have soil C data. N balance is the difference between the sum of total N inputs from fertilizer, manure, compost, and legume N fixation, and the N exported in all harvested crops. Briefly, we will use data from each site on yield and % N of grain (or forage, stover) to estimate N removed from fields in harvested crops. If these data are not available for a given site, we will use mean values from the NRCS Crop Nutrient Tool [50] or mean values from similar sites. N inputs from fertilizer and manure will be calculated from long-term management records (e.g., manure rates combined with manure N concentration). Legume N inputs will be estimated as explained in the methods for Question 1. We will model partial N balance for all sites as a function of SOC stock (e.g., g C m^2) and N source along with environmental factors. Finally, we will run a model with N losses (NO_3^- leaching and N_2O flux) as the dependent variable for sites that have measured them over time.

Question 3: **How does global warming potential vary across the crop diversification gradient?**

Hypotheses: We hypothesize that global warming potential will decrease with increasing cropping system diversification and total NPP. However, there will be trade-offs with crop yield because higher diversity systems may have lower yields of annual grain crops.

Methods: We will quantify global warming potential (GWP; [51]) in CO_2 equivalents (CO_2e) for the same measurement period as change in SOC at each site following the methods in Gelfand and Robertson [7], which used a mass balance approach to show that the conventional system had positive GWP (net emitter of GHGs) while mitigation potential strongly increased from no-till to organic management systems. Specifically, GWP accounts for measured and estimated GHG fluxes into and out of each management system, expressed as CO_2e. Key components of the balance include changes in SOC, estimated emissions from inputs including fertilizers, lime, and fuel for farm operations, and GHG emissions from soil (CO_2, N_2O, and CH_4). We will quantify GWP for the crop diversification index and for distinct management systems (e.g., conventional, organic). We will also express GWP per unit productivity (NPP) for a complete crop rotation cycle and per harvested crop yield for each system. Although a substantial literature documents the GWP of individual management practices [52], we lack estimates for complete management systems that combine suites of practices [7]. We will update the earlier analysis for KBS to include the past decade and extend this approach to other sites based on available data. Across sites, we will test for differences in GWP by management, controlling for environmental conditions, using linear mixed-models in R.

Incorporating stakeholder feedback: The proposed project will address compelling and policy-relevant research needs related to soil C sequestration. We will leverage Roundtable Meetings planned for a related USDA project (PI Blesh) to integrate stakeholder engagement in the early project stages (see letter from Dr. Julie Doll). The Roundtables are convening diverse stakeholders including farmers, Cooperative Extension educators, conservation technicians, and the policy community, and have led to productive discussions that are building trust and long-term relationships with the agricultural community in our region. The third Roundtable, to be held in December 2022, has a planned focus on C sequestration, which strongly aligns with this proposal. We will adapt the agenda to include the proposed project, sharing information on the long-term sites we are including, available data, and the planned research questions and analytical approach to solicit feedback, which we will then incorporate into our research. We expect these activities will extend the impact of our research by helping to guide our approach and produce actionable results. After the modeling is complete, we will report back to the Roundtable participants for their feedback. We will also travel to a subset of the long-term sites included in the study to share findings, gain feedback on our interpretation, and plan future research collaborations.

Expected outcomes

Agriculture directly contributes 10-14% of the emissions that cause climate change [53]. Diversified cropping systems are understudied, but a growing body of evidence indicates their strong potential to restore SOC while providing a broad suite of other ecosystem services. In addition, recent passage of the Growing Climate Solutions Act, which supports expansion of C markets, presents new opportunities for increasing the financial viability of diversified cropping systems. Yet, effectively incorporating these practices into policies requires stronger empirical data to scale up understanding of their potential outcomes. Our proposed project will address this gap, and advance the science behind emerging C markets, through three primary outcomes: (1) determining the N requirements of soil C sequestration for management systems spanning a diversification gradient, including ecological practices that currently receive minimal policy support, but are more likely to increase multiple ecosystem services; (2) identifying key thresholds of SOC at which N losses are reduced and N is retained, which can inform cost share and crediting schemes that lead to net environmental benefits for N and C retention in soil; (3) developing a whole-systems approach to quantify the GWP of distinct management systems. By collating data from multiple long-term sites in the U.S. Midwest, and advancing scientific understanding of the N demands of SOC accrual along a diversification gradient, this project will produce policy-relevant results and a valuable database for extending this work to additional sites and research questions.

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Project Timeline

Project Year	2022			2023				2024
Quarter	2	3	4	1	2	3	4	1
Identify additional long-term sites to include in study								
Compile data from all sites and build database								
Quantify metrics of cropping system diversification								
Calculate other variables for models (e.g., SALUS model for nitrate leaching at KBS; legume N inputs; partial N balances)								
Solicit input on initial research plan at Roundtable Meeting in MI								
Calculate Global Warming Potential for all management systems								
Develop and run initial models to address research questions 1-3								
Submit interim project report to EDF								
Present preliminary results at the ESA annual meeting								
Complete modeling activities and finalize results								
Share results in LTAR working group meeting for feedback								
Visit a subset of sites to share results, discuss interpretation								
Present findings at the AGU annual meeting								
Prepare 2-3 manuscripts and submit to journals								
Submit final report to EDF								

Deliverables

As listed in the timetable, we will produce the following deliverables: (1) interim and final reports to EDF; (2) 2-3 manuscripts (e.g., one per research question) targeting high-impact, peer-reviewed journals reaching ecological and agricultural audiences (e.g., *Global Change Biology*; *Agriculture, Ecosystems and Environment*; *BioScience; Nature Sustainability; Environmental Research Letters*); (3) conference presentations at the Ecological Society of America annual meeting (August 2023) and the American Geophysical Union annual meeting (December 2023); (4) stakeholder feedback from presentations at the Roundtable Meeting and reporting back to participating long-term experimental sites; (5) an open access database that can be used by the PIs and others to extend the proposed analysis to additional sites and management systems, and to update the dataset as new data become available over time.

Harnessing long-term data to understand the N demands of soil C sequestration across a crop diversification gradient
PI Jennifer Blesh; Co-PI Brendan O'Neill
03/01/2022-02/28/2024

	Budget Period	3/1/22-2/28/23	3/1/23-2/28/24	
		YEAR 1	YEAR 2	TOTAL
Salaries		3/1/22-2/28/23	3/1/23-2/28/24	
114,190	PI Blesh		13,068	13,068
79,568	Co-PI O'Neill	46,414	81,955	128,369
$16/hr	Res. Asst.	8,960	3,200	12,160
		55,374	**98,223**	**153,597**
Fringe Benefits				
	PI Blesh	-	3,920	3,920
	Co-PI O'Neill	13,924	24,586	38,510
	Res. Asst.	685	245	930
		14,609	**28,751**	**43,360**
TOTAL SALARIES & BENEFITS		***69,983***	***126,974***	***196,957***
Domestic Travel		-	3,000	3,000
Publications		-	3,000	3,000
TOTAL OTHER DIRECT COSTS		**-**	**6,000**	**6,000**
TOTAL DIRECT COSTS		***69,983***	***132,974***	***202,957***
MODIFIED TDC / IC BASE		69,983	132,974	202,957
INDIRECT COSTS		***10,497***	***19,946***	***30,443***
TOTAL COSTS		***80,480***	***152,920***	***233,400***
Indirect Costs Rates		15.0%	15.0%	

Budget Justification

Salaries

PI Jennifer Blesh: In Year 2 we request support for one summer month salary support for PI Blesh. PI Blesh will be responsible for overall project oversight, reporting to EDF, and coordinating activities with the Co-PI and research assistant.

Co-PI Brendan O'Neill: In Year 1-2 support is requested for 7 calendar year months effort (58%) for Co-PI O'Neill. This represents the effort level required to complete the proposed work, which will be his primary research focus during this period. Co-PI O'Neill will be responsible for building the database and completing proposed modeling activities, with assistance from PI Blesh and from a graduate student research assistant. O'Neill will serve as the primary supervisor for the research assistant.

Research Assistant: We will recruit a graduate student research assistant from the University of Michigan School for Environment and Sustainability at the start of the project. Compensation for the research assistant is estimated at $16/hour. We estimate the research assistant will devote 20 hours per week for 28 weeks in Year 1, and 20 hours per week for 10 weeks in Year 2 to help collate data from the long-term sites and build the database (e.g., assisting with finding literature values for the N mass balances and for the analysis of global warming potential, parameterizing SALUS for sites with soil nitrate data, etc.).

Fringe Benefits

Fringe benefits for PI Blesh and Co-PI O'Neill are estimated at a rate of 30% of salary costs. Fringe benefits for the research assistant are estimated at a rate of 7.65% of salary costs. The standard University of Michigan benefits package includes health care, dental, vision, and retirement contribution.

Travel

Support is requested for $3,000 in domestic travel in Year 2. This budget support will allow the project team to share findings at two scientific conferences (ESA and AGU) and to travel to share findings at participating sites that are not within easy driving distance of Michigan (e.g., Iowa, Missouri). Travel budget request includes support for airfare ($1,500), lodging ($1,125), and per diem ($375).

Publication

Support is also requested for $3,000 in publication expenses. This budget support will allow the project team to disseminate the results of the research project, including through one open access publication.

Indirect Costs

Indirect costs, at a rate of 15% of all direct costs, are requested on this research grant. Total indirect costs requested for both years of the project period are $30,443.

Total Costs

Total costs requested, including all direct and indirect costs, are $233,400.

Collaborator roles and biosketches

Dr. Jennifer Blesh (PI) is an associate professor in the School for Environment and Sustainability (SEAS) at the University of Michigan (UM) trained in ecosystem ecology, agroecology, and soil science. As PI, she will be responsible for overall management and coordination of the project, including the budget and interim and final reports to EDF. She will achieve the proposed objectives in close collaboration with the research scientist who will lead the data compilation and analysis activities, with assistance from a graduate student in SEAS. Blesh will be closely involved in building relationships with researchers at sites where the team has not previously worked, analyzing data, preparing manuscripts for publication, and preparing presentations to share this work with other researchers and a diverse group of stakeholders. Results from this project will support future grant proposals for long-term, interdisciplinary, and collaborative research, including through the USDA Long-term Agroecosystem Research (LTAR) network. Blesh serves on the Design Team for the new LTAR experiment at Kellogg Biological Station (KBS), where she has previously led experiments supported by funding from the USDA AFRI Foundational program. She is also a member of the LTAR network soils working group.

Dr. Brendan O'Neill (Co-PI) is an assistant research scientist in SEAS at UM with training in soil microbial ecology and ecosystem ecology with an emphasis on greenhouse gases. His position is largely grant-funded, and he will lead the database creation and data analysis activities on the proposed project as his primary research focus during the project period. He has previously worked at the KBS LTER site through his dissertation research at Michigan State University, which included projects on the resource gradient and biodiversity gradient experiments at KBS.

Through initial conversations with researchers at sites listed in the proposal, we expect most data needed for this project to be publicly available with approval of data owners and proper acknowledgement. However, we will invite other individuals from the included sites to collaborate and co-author components of the proposed analysis based on their interest and desired level of involvement.

Jennifer Blesh
School for Environment and Sustainability, Sustainable Food Systems Initiative,
University of Michigan (UM), Ann Arbor, MI 48109; jblesh@umich.edu

Education

University of Georgia	Ecology	B.S.	2003
Cornell University	Soil and Crop Sciences	M.S.	2008
Cornell University	Soil and Crop Sciences	Ph.D.	2012

Experience and Positions

2020 – present	Associate Professor, School for Environment and Sustainability, UM
2014 – 2020	Assistant Professor, School for Environment and Sustainability, UM
2011 – 2013	National Science Foundation IRFP Post-Doctoral Fellow: Federal University of Mato Grosso, Cuiabá, MT, Brazil
2005 – 2011	Graduate Research Assistant, Cornell University, Ithaca, NY

Selected publications relevant to proposed work (*Advisees)

Stratton, A.E., Comin, J.J., Siddique, I., Zak, D.R., Filipini, L., Lucas, R.R., and J. **Blesh**. (*In Revision*). Assessing cover crop and intercrop performance along a farm management gradient. *Agriculture, Ecosystems and Environment*.

Herrick, E. and J. **Blesh**. 2021. The importance of intraspecific trait variation in cover crops. *Ecosphere*. https://doi.org/10.1002/ecs2.3817.

Bressler, A., Plumhoff, M., Hoey, L., and J. **Blesh**. 2021. Cover Crop Champions: Linking strategic communication approaches with farmer networks to support cover crop adoption. *Society and Natural Resources*. doi: 10.1080/08941920.2021.1980165

Stratton, A.E., Wittman, H., and J. **Blesh**. 2021. Diversification supports farm income and improved working conditions during agroecological transitions in southern Brazil. *Agronomy for Sustainable Development*. https://doi.org/10.1007/s13593-021-00688-x

Stratton, A.E., Kuhl, L., and J. **Blesh**. 2020. Ecological and nutritional functions of agroecosystems as indicators of smallholder resilience. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2020.543914.

Blesh, J. and T. Ying. 2020. Soil fertility status controls the decomposition of litter mixture residues. *Ecosphere* 11(8):e03237. doi: 10.1002/ecs2.3237.

Zimnicki, T., Boring, T., Evenson, G., Kalcic, M., Karlen, D., Zhang, Y. and J. **Blesh**. 2020. On quantifying water quality benefits of healthy soils. *BioScience* 70: 343-352.

Jain, M., Singh, B., Rao, P., Srivastava, A.K., Poonia, S., **Blesh**, J., Azzari, G., McDonald, A.J., and D.B. Lobell. 2019. Using satellite data to evaluate and target sustainable intensification interventions can double their impact. *Nature Sustainability* 2: 931-934.

Blesh, J. 2019. Feedbacks between nitrogen fixation and soil organic matter increase ecosystem functions in diversified agroecosystems. *Ecological Applications* 29(8): https://doi.org/10.1002/eap.1986

Bukovsky-Reyes, S., Isaac, M., and J. **Blesh**. 2019. Effects of intercropping and soil properties on root functional traits of cover crops. *Agriculture, Ecosystems, and Environment*: https://doi.org/10.1016/j.agee.2019.106614.

Blesh, J., VanDusen, B.M., and D.C. Brainard. 2019. Managing ecosystem services with cover crop mixtures. *Agronomy Journal* 111: 826-840.

Blesh, J. Hoey, L., Jones, A.D., Perfecto, I. and H. Friedmann. 2019. Development pathways toward "zero hunger." *World Development* 118: 1-14.

Zak, D.R., Pellitier, P.T., Argiroff, W.A., Castillo, B., James, T.Y., Nave, L.E., Averill, C., Beidler, K., Bhatnagar, J., **Blesh**, J., Classen, A.T., Craig, M., Fernandez, C.W., Gunderson, P., Johansen, R., Koide, R., Lilleskov, E.A., Lindall, B.D., Nadelhoffer, K., Phillips, R.P., and A.

Tunlid. 2019. Exploring the function of ectomycorrhizal fungi in soil organic matter dynamics. *New Phytologist*. https://doi.org/10.1111/nph.15679.
King, A. E. and J. **Blesh**. 2018. Crop rotations for increased soil carbon: perenniality as a guiding principle. *Ecological Applications* 28: 249-261.
Blesh, J. 2018. Functional traits in cover crop mixtures: biological nitrogen fixation and multifunctionality. *Journal of Applied Ecology*. 55: 38-48.
Schipanski, M.E., MacDonald, G.K., Rosenzweig, S., Chappell, M.J., Bennett, E.M., Bezner Kerr, R., **Blesh**, J., Crews, T., Drinkwater, L.E., Lundgren, J., and C. Schnarr. 2016. Realizing resilient food systems. *BioScience* 66: 600-610. doi:10.1093/biosci/biw052.
Crews, T.E., **Blesh**, J., Culman, S.W., Hayes, R.C., Jensen, E.S., Mack, M.C., Peoples, M.B., and M.E. Schipanski. 2016. Going where no grains have gone before: from early to mid-succession. *Agriculture, Ecosystems and Environment* 223: 223-238. https://doi.org/10.1016/j.agee.2016.03.012.
Blesh, J. and S.A. Wolf. 2014. Transitions to agroecological farming systems in the Mississippi River Basin: toward an integrated socioecological analysis. A*griculture and Human Values* 31:621-635. doi: 10.1007/s10460-014-9517-3.
Blesh, J. and L.E. Drinkwater. 2014. Retention of ^{15}N-labeled fertilizer in an Illinois prairie soil with winter rye. *Soil Science Society of America Journal* 78:496-508. doi:10.2136/sssaj2013.09.0403.
Blesh, J. and L.E. Drinkwater. 2013. The impact of nitrogen source and crop rotation on nitrogen mass balances in the Mississippi River Basin. *Ecological Applications* 23(5):1017-1035. https://doi.org/10.1890/12-0132.1.
Gardner (Blesh) J. and L.E. Drinkwater. 2009. The fate of nitrogen in grain cropping systems: a meta-analysis of ^{15}N field experiments. *Ecological Applications* 19(8): 2167-2184. https://doi.org/10.1890/08-1122.1.

Current Teaching and Mentoring

Foundations of Sustainable Food Systems (ENVIRON 462/EAS 528)

Agroecosystem Management: Nutrient Cycles and Soil Fertility (EAS 524)

Currently serve as primary advisor for 2 postdoctoral fellows and 7 PhD and MS students

Selected Grants and Fellowships

2021-2024 “Harnessing perennial grain-legume intercrops for agroecosystem sustainability” USDA AFRI: Foundational Program. Role: PI
2021-2022 “Diversifying cover crops to sequester carbon in agricultural soils” Graham Institute: Carbon Neutrality Acceleration Program. Role: PI
2019-2021 “Linking plant traits with soil health to determine optimal cover crop mixtures on organic farms” USDA NIFA: Organic Transitions. Role: PI
2019-2021 “Ecosystem services from cover crops: Management legacy effects from field to landscape scales.” USDA AFRI: Foundational Program. Role: PI
2019-2021 “Next generation cover crops: driving innovation in soil management with participatory certification.” Conservation, Food and Health Foundation. Role: Co-PI; led by a non-profit partner in Santa Catarina, Brazil, CEPAGRO
2015-2018 “Legume cover crop impacts on soil nitrogen cycling and soil fertility on organic vegetable farms” Ceres Trust, Organic Research Initiative. Role: PI

Synergistic Professional Activities

PI on two USDA-funded projects focused on cover crop mixtures and soil organic matter, at the KBS LTER site, and on 15 working farms in two regions of Michigan.

PI on a recently completed Ceres Trust-funded project on legume cover crops, biological nitrogen fixation, and soil health on 10 organic vegetable farms in Michigan. Resulted in 5 publications.

Gave 12 invited presentations from 2018 – 2021 at universities and conference symposia on my research, including the keynote address– *Learning from farmers: Diversifying crop rotations to make farms more resilient* – at the Practical Farmers of Iowa Conference in Springfield Illinois in 2020.

Invited participant at relevant workshops: (1) 2018- Cooperative Institute for Great Lakes Research (CIGLR). Improving Models of Nutrient Loading and Harmful Algal Blooms through a Watershed-Scale Approach that Emphasizes Soil Health and Upland Farming Practices, The University of Michigan; (2) 2018- Beyond Carbon Neutral. *Enhancing Long-Term Soil C Sequestration by Ectomycorrhizal Fungi*, The University of Michigan; and (3) 2016- Environmental Defense Fund. *Data Needs for Implementing an N Surplus Framework in EDF's Supply Chain Work*. Washington, D.C.

Co-PD on a USDA Higher Education Challenge (HEC) grant (2016-201) and a USDA NIFA National Needs Fellowship grant (2021-2025), both of which aim to increase the number and diversity of students in the growing Sustainable Food Systems academic program at the University of Michigan and enhance student learning through experiential education with local community food and agriculture organizations.

Brendan O'Neill
School for Environment and Sustainability, Sustainable Food Systems Initiative,
University of Michigan, Ann Arbor, MI 48109; obrendan@umich.edu

Education

Indiana University	Biology	B.S.	2000
Cornell University	Crop and Soil Sciences	M.S.	2007
Michigan State University	Soil, Crop and Microbial Sciences	Ph.D.	2017

Experience and Positions

2020 – Present	Assistant Research Professor, School for Environment and Sustainability, University of Michigan
2017 – 2019	Post-Doctoral Fellow, Lecturer and Visiting Scholar, W. K. Kellogg Biological Station, Michigan State University
2010 – 2017	Graduate Research Assistant, Soil, Crop and Microbial Sciences, Michigan State University
2007 – 2009	Research technician Crop and Soil Sciences, Cornell University, Ithaca, NY

Synergistic Professional Activities

USDA SARE graduate research grant testing soil health across Michigan farms. We used farmer knowledge of field variability to determine how well soil health tests matched farmer field assessments.

PI on a project funded by the Graham Institute at the University of Michigan assessing soil health and ecosystem services on land under solar energy development in Michigan. Along with soil data collection, we are facilitating discussions with a new network of leaders in solar development, agriculture, and conservation to understand how the growth of solar can interface with sustainable land use, including diversified agricultural practices.

Ongoing work from post-doc analyzing rRNA sequenced from year-long incubations of soil from bioenergy field plots in a long-term experiment, assessing carbon accrual and turnover in different treatments, and soil microbial communities associated with plant communities and feedstocks.

Gave 12 formal presentations from 2017 – 2021 at universities and conference symposia on my research, including *Linking soil C and N cycling and trace gas fluxes with soil bacterial communities along a* *gradient of simple to complex crop rotations*– at a symposium at the Soil Ecological Society in 2017, and – *Solar on agricultural soils: Identifying opportunities and challenges for sustainable energy and Land Use.* – Northern Michigan Small Farms Conference. In Traverse City, MI, 2021.

Co-PD on a USDA NIFA National Needs Graduate and Postgraduate Fellowship Grant, aimed at drawing underrepresented students for study at the University of Michigan as part of the Sustainable Food Systems Initiative. 2021-2025.

Selected Grants and Fellowships

2021-2025 "Transformative food systems fellows program: cultivating resilient agriculture" USDA NIFA National Needs Graduate and Postgraduate Fellowship Grant. Role: Co-PI

2020 – 2021 "Innovating Agrivoltaic Systems for the Great Lakes Region" Graham Sustainability Institute, University of Michigan. Role: PI

2019-2021 Review of the state knowledge on agroecological liquid bio-inputs with a special focus on the Andes McKnight Foundation Collaborative Crop Research Program. Role: PI

2014-2015 GK-12 Bioenergy Sustainability Project Fellowship, NSF

2014-2015 USDA-SARE Graduate Student Research Grant

2014 Kellogg Biological Station Summer Research Fellowship

2010-2013 C.S. Mott Pre-doctoral Fellowship in Sustainable Agriculture

Relevant Publications:

In prep **O'Neill, B**. Gross, K., A.S., Robertson, G.P. Potentially mineralizable soil nitrogen and leaf chlorophyll in maize growth with different rotational histories. *Applied Soil Ecology*.

In prep **O'Neill, B**. Grandy, A.S., Robertson, G.P., Kravchenko, A. H. Juottonen, H., Schmidt, T.M. Legume cover crops alter microbial controls on soil denitrification rates and efficiency. *Biogeochemistry.*

In review **O'Neill, B**. Grandy, A.S., Robertson, G.P., Kravchenko, A., Schmidt, T.M. Cover crops increase rotational complexity to shift microbial carbon processing and accrual in soil. *Ecosphere*.

2021 **O'Neill, B**., Sprunger, C.D., Robertson, G.P. Do soil health tests match farmer experience? Assessing biological, physical, and chemical indicators in the Upper Midwest United States. Soil Science Society of America Journal. https://doi.org/10.1002/saj2.20233

2010 Grossman, J.M.; **O'Neill, B.**; Tsai, S.M. Thies, J.E., PCR-DGGE analysis identifies novel Archaea and Eubacteria in anthropogenic *Terra Preta* soils of the Brazilian Amazon. Microbial Ecology, 60:192-205.

2010 Biqing L., Lehmann J., Sohi S., Thies, J.E., **O'Neill, B.,** Trujillo, L., Gaunt, J., Solomon, D., Grossman, J., Neves, E. G., Luizão, F.J. Black carbon affects the cycling of non-black carbon in soil. Organic Geochemistry, 41 (2010) 206-213.

2009 **O'Neill, B**., Grossman, J., Tsai, S.M., Gomes, J.E., Lehmann, J., Peterson, J., Neves, E., Thies, J.E. Microbial community composition in Brazilian Anthrosols and adjacent soils using culturing and molecular identification. Microbial Ecology, 58: 23-35.

2009 Tsai, S.M., **O'Neill**, **B**., Cannavan, F.S., Saito, D., Falcão, N.P.S., Kern, D. Grossman, J., Thies, J. The microbial world of *Terra Preta*. *In* Amazonian Dark Earth: Wim Sombroek's Vision, edited by Woods, W.I., Teixeira, W.G., Lehmann, J., Steiner, C., WinklerPrins, A., Rebellato, L. Springer, Berlin.

2007 Vadas, T.M.; Fahey, T.J.; Sherman R.E.; Demers, J.D.; Grossman, J.M.; Maul, J.E.; Melvin, A.M.; **O'Neill, B.;** Raciti, S.M.; Rochon, E.T.; Sugar, D.J.; Tonitto, C.; Turner, C.B.; Walsh, M.J.; Zue, K. Approaches for analyzing local carbon mitigation strategies: Tompkins County, New York, USA, International Journal of Greenhouse Gas Control, 1 (3): 360-373.

2006 Liang B., Lehmann, J., Solomon, D. Kingyangi, J., Grossman, J.M. **O'Neill, B**., Skjemstad J.O., Thies J., Luizão, F.J., Petersen, J. Neves, E.G.. Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal. 70 (5): 1719-1730.

MICHIGAN STATE UNIVERSITY

W.K. Kellogg Biological Station

3700 E. Gull Lake Dr.
Hickory Corners, MI 49060

269-671-5117
Fax: 269-671-2351
kbs.msu.edu

January 4, 2022

Dr. Jennifer Blesh
Dr. Brendan O'Neill
University of Michigan
School for Environment and Sustainability
440 Church St.
Ann Arbor, MI 48109

RE: Support letter for Environmental Defense Fund proposal

Dear Drs. Blesh and O'Neill,

I would like to communicate my enthusiastic support for your proposal to the Environmental Defense Fund entitled "Harnessing long-term data to understand the N demands of soil C sequestration across a crop diversification gradient." Your intent to better understand the rate of soil C sequestration per unit N input – for a range of long-term sites in the Midwestern U.S., and for a range of N sources and management systems – provides a perfect complement to our long-term experiments and research on ecosystem services and agriculture.

I would be happy to support you on this research, and facilitate your access to long-term data (from 1989) on total soil organic C to 1 m depth, crop yields, fertilizer N inputs, legume cover crop biomass, soil nitrate concentrations, and nitrous oxide emissions from our LTER Main Cropping Systems Experiment (http://lter.kbs.msu.edu/research/long-term-experiments/main-cropping-system-experiment/).

As LTER investigators you will have full access to data generated by the KBS LTER program, including our net primary production, soil chemistry and biology, and weather databases, as well as access to our soil, plant, and microbial sample archives. We can also provide data management support needed to make the information we generate available on the KBS LTER web site (http://lter.kbs.msu.edu).

Good luck with the proposal – it sounds like a great project and we look forward to its initiation.

Sincerely,

Nick Haddad
Director, Kellogg Biological Station Long Term Ecological Research Site

MSU is an affirmative-action
equal-opportunity employer.

January 3, 2022

Dr. Jennifer Blesh
University of Michigan
School for Environment and Sustainability
440 Church St.
Ann Arbor, MI 48109

RE: Support letter for Environmental Defense Fund proposal

Dear Dr. Blesh,

I am writing in support of your proposal to the Environmental Defense Fund entitled "**Harnessing long-term data to understand the N demands of soil C sequestration across a crop diversification gradient.**" I am excited by the prospect of integrating this project into the series of Roundtable Meetings we are currently organizing with you for your complementary USDA AFRI project on ecosystem services from cover crops.

Michigan Agriculture Advancement (MiAA) is an organization that works to improve the economic, social, and environmental sustainability of agriculture across the Great Lakes region. The complexity of nitrogen and carbon dynamics in cropping systems is of great interest to the farmers and agricultural professionals MiAA works with. We will tap into our networks to recruit participants for this Roundtable Meeting, as well as share project reports more broadly over time.

I would be happy to support your efforts to take an interactive, co-generation of knowledge approach to your proposed research. Specifically, we can adapt the agenda of the final Roundtable meeting planned for your related USDA award to integrate stakeholder perspectives into the proposed project. This meeting, planned for December 2022, will convene a diverse array of stakeholders, including farmers, Cooperative Extension educators, conservation agency personnel, and private sector advisors (e.g., Certified Crop Advisors). The specific topic of this Roundtable is soil organic carbon storage, and it will therefore work well to incorporate the proposed project into the meeting agenda. Based on your proposed timeline, you can share details on the types of long-term experimental data available (i.e., the sites, management systems, ranges of SOC, N inputs for fertilizer, legumes, and manure), and the main questions and analyses you intend to pursue. This will allow you to solicit stakeholder feedback at an early project stage, which can inform the subsequent modeling approach and help produce results that are directly relevant to farmers and policymakers.

I am excited by the data-driven, actionable research questions proposed here. Your research outcomes will provide valuable information that can advance our efforts to expand the presence of farming systems that improve environmental sustainability and the prosperity of our rural communities.

Sincerely,

Julie E. Doll

Julie E. Doll, PhD
CEO, Michigan Agriculture Advancement

THE OHIO STATE UNIVERSITY

College of Food, Agricultural, and Environmental Sciences

School of Environment and Natural Resources

130 Williams Hall
1680 Madison Ave
Wooster, OH 44691

330-263-3787
culman.2@osu.edu

January 2, 2022

Dr. Jennifer Blesh
Dr. Brendan O'Neill
University of Michigan
School for Environment and Sustainability
440 Church St.
Ann Arbor, MI 48109

RE: Support letter for Environmental Defense Fund proposal

Dear Drs. Blesh and O'Neill,

I write in enthusiastic support for your proposal to the Environmental Defense Fund entitled *"**Harnessing long-term data to understand the N demands of soil C sequestration across a crop diversification gradient.**"* The Triplett-Van Doran (TVD) experiment at The Ohio State University is a tillage and crop rotation trial ideally suited to address core questions related to long term soil carbon and nutrient management. The TVD is the longest no-till experiment in existence, maintained contentiously for sixty years, alongside two other tillage treatments, all in a two-way factorial design with three crop rotations – continuous corn, corn+soy, corn+oat+hay - with all phases of each rotation, on two locations with different soil types.

My lab currently maintains and manages data from the TVD trials. I am keen to facilitate access to these data as part of a broader effort to understand how management for soil carbon sequestration impacts soil N dynamics. The TVD trial has detailed yield, weather, tillage, and agronomic data (e.g. nitrogen sources, application rates and timing) as well as soil parameters such as total C and N, collected at regular intervals since 1962, as well as some other soil health data.

Good luck with the proposal – I look forward to helping use data from the TVD to answer critical questions in long term management of soil carbon and nutrient resources in the Midwest.

Sincerely,

Steve W Culman

Steve Culman, Ph.D.
Associate Professor of Soil Fertility
School of Environment and Natural Resources
130 Williams Hall
1680 Madison Ave
Wooster Ohio, 44691
(330) 263-3787
culman.2@osu.edu
http://soilfertility.osu.edu

United States Department of Agriculture

Research, Education, and Economics
Agricultural Research Service

January 3, 2022

Dr. Jennifer Blesh
Dr. Brendan O'Neill
University of Michigan
School for Environment and Sustainability
440 Church St.
Ann Arbor, MI 48109

RE: Support letter for Environmental Defense Fund proposal

Dear Drs. Blesh and O'Neill,

I am writing in support of your proposal to the Environmental Defense Fund entitled "**Harnessing long-term data to understand the N demands of soil C sequestration across a crop diversification gradient.**" By quantifying the rate of soil C sequestration per unit N input across long-term experimental sites in the Midwestern U.S., with an emphasis on understanding the role of N source and crop rotation diversity, your project will strongly complement our existing data compilation and synthesis efforts for the LTAR network in the U.S.

Over the past year and a half, I have led the USDA-LTAR soils working group, which has recently completed a data inventory and harmonization assessment among 18 LTAR research regions. This effort created the framework to facilitate data access for USDA projects from the LTAR network as well as other USDA research facilities and collaborators. The project described here by Drs. Blesh and O'Neill complements this effort, and can be supported by connecting their team with the three midwestern LTAR sites: Upper Mississippi River Basin (UMRB, Sharon Weyers), Central Mississippi River Basin (CMRB, Kristen Veum), and the Eastern Corn Belt (ECB, Will Osterholtz). These sites have numerous long-term projects in place that will have useful carbon and nitrogen input data for this project. The researchers can work out the specific details of data protocols and processing through further discussions.

We also hope that this project will lead to future proposals and collaborations addressing related research questions for all sites within the LTAR network.

Sincerely,
Dr. Jude Maul

Jude Maul

Research Ecologist, USDA-ARS
Sustainable Agricultural Systems Lab
10300 Baltimore Ave. Bldg. 001 rm. 123
Beltsville, MD 20705
jude.maul@usda.gov