Received: 15 March 2024 | Accepted: 2 April 2024

DOI: 10.1002/ael2.20128

Agricultural & Environmental Letters OPEN ACCESS

RESEARCH LETTER

Soil health indicators reveal that past dairy manure applications create a legacy effect

David D. Tarkalson | **Christopher W. Rogers** | **David L. Bjorneberg** | **Robert S. Dungan**

USDA-ARS, Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho, USA

Correspondence
David D. Tarkalson, USDA-ARS, Northwest Irrigation and Soils Research Laboratory, Kimberly, ID, USA.
Email: david.tarkalson@usda.gov

Assigned to Associate Editor Zhongqi He.

Abstract

Understanding the long-term effects of manure applications on the soil microbial component in semiarid climates will be key to sustain essential processes that affect their productivity and soil health. In this paper, soil health indicators encompassed both selected chemical and biological indicators. From 2004 to 2009, solid dairy manure treatments were applied to plots at cumulative rates of 0, 134, and 237 dry Mg ha^{-1} (34–56 dry Mg ha^{-1} year^{-1}) in a randomized complete block with three replicates. Soil samples were taken from each manure rate in the spring of 2020 at 0–15 and 15–30 cm. Eleven years after manure applications ceased, many of the soil chemical and biological indicators were different between the manure and control treatments. In general, soil organic carbon and biological indicators were significantly greater in the 134 and 237 Mg ha^{-1} treatments as compared to the 0 Mg ha^{-1} treatment.

1 | INTRODUCTION

In the United States, Idaho is currently the third largest dairy milk producer, with a total of 661,000 lactating cows (USDA-NASS, 2023). In the past three decades, Idaho total herd size has increased by approximately 242%, with most of the production (~71%) occurring in the south-central part of the state known as the Magic Valley. Given that an average lactating cow produces 58 kg manure day^{-1}, Idaho producers must manage a total of nearly 3.8×10^7 kg manure day^{-1}. Because the majority of this manure is land applied, there is a need to focus additional research on manure and nutrient management (He et al., 2016; Leytem et al., 2021), as well as on other potential negative environmental implications (Dungan et al., 2023; McKinney et al., 2018).

Few studies have been conducted to assess the effects of cattle manure (beef or dairy) on soil health indicators (chemical and biological) in irrigated semiarid cropping systems (Dungan et al., 2022; Elzobair et al., 2016; Lupwayi et al., 2019; Miner et al., 2020). In southern Idaho, Dungan et al. (2022) found that enzyme activities and N transformation rates were significantly greater in soils amended with high rates of dairy manure for several years. In the semiarid environment of Lethbridge, Canada, Lupwayi et al. (2019) reported that increased enzyme activities could be detected decades after the last beef cattle manure application, with significantly greater microbial biomass and enzyme activity under irrigated versus rainfed conditions. Other research conducted in irrigated croplands in Idaho has demonstrated that soils receiving dairy manure have different soil chemical properties and crop yields and quality compared to non-manured soils (Baxter et al., 2023; Robbins et al., 1997).

The legacy effects of cattle manure solids can be attributed to increases in SOC followed by the release of nutrients via

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microbial mineralization, which can occur for long periods of time after the last manure application (Indraratne et al., 2009; Larney et al., 2016; Meek et al., 1982). However, additional research is required to better understand the long-term effects of manure, especially in irrigated semiarid climates in the western United States. The objective of this study was to evaluate the effect of past dairy manure applications on selected soil health indicators (chemical and biological) in an irrigated field 11 years after the last manure application. A specific emphasis was placed on the use of enzyme indicators and N transformation rates, as these biological measurements are sensitive to changes in management (Stott, 2019). This study builds upon previous research at a field site in Kimberly, ID (Tarkalson et al., 2018) and it will be used to advance our understanding of the unique long-term influence that dairy manure imparts upon soil health properties in semiarid southern Idaho.

2 | MATERIALS AND METHODS

The field study was initiated in 2004 at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID, on a Portneuf silt-loam (coarse-silty mixed superactive and mesic Durixerollic Calciorthids). Treatments consisted of solid dairy manure (open-lot scrapings) at cumulative dry application rates of 0, 134, and 237 Mg ha^{-1} (referred to as 0, 134, and 237 Mg, respectively). Each treatment was replicated three times in a randomized complete block design. The manure was applied from 2004 to 2009 to field plots of 0.1 ha at annual rates ranging from 34 to 56 dry Mg ha^{-1}. During this time, the 0 Mg treatment (i.e., non-manured control) received synthetic commercial fertilizer based on soil tests and published recommendations (Brown et al., 2010; Moore et al., 2012; Robertson & Stark, 2003; Walsh et al., 2019). From 2010 to 2019, all treatments were uniformly applied with regard to cropping, fertilizer, irrigation, and other cultural practices. Conventional tillage occurred each year from 2004 to 2020. The main conventional tillage practices used in a given year were either disk and roller harrow or moldboard plow and roller harrow.

Soil samples were collected in the spring of 2020 prior to fertilization and crop planting. From each plot, six soil cores (0–15 cm and 15–30 cm) were collected and composited by depth and thoroughly mixed. Field moist subsamples were sieved (2 mm), then a portion was immediately placed into a clean sealable plastic bag and refrigerated at 5˚C, while the other portion was air-dried, then placed into a clean sealable plastic bag. Soil biological analyses on field moist soils were completed within 2 weeks of the sampling time. The soil samples were analyzed according to chemical and biological procedures listed in Table 1.

Core Ideas

- Dairy manure has long-term effects on soil health indicators in southern Idaho semiarid irrigated soils.
- Dairy manure last applied 11 years prior to soil sampling increased many of the soil health indicators.
- Soil biological indicators can be effectively utilized to understand the legacy effects of manure.

Statistical analysis was conducted in Statistix 10 (Analytical Software). Analysis of variance (ANOVA) was conducted for manure history main effect for soil health indicators. Significance was determined at $\alpha = 0.1$. For significant ANOVA effects, mean separation was conducted using the least significant difference method.

3 | RESULTS AND DISCUSSION

Eleven years after manure applications ceased, many of the soil health indicators were different between treatments, despite the uniformity of management practices from 2010 to 2019 (Table 2). In general, enzyme activities and N transformation rates were significantly greater in the 134 and 237 Mg treatments as compared to the non-manured control. Therefore, it is evident that manure applications had a long-term or legacy effect (at least 11 years post manure application) on soil health indicators, especially those related to nutrient cycling (Table 2).

3.1 | Chemical properties

The manure treatments had a significant effect on SOC at 0–30 cm, where the SOC concentrations increased with increasing manure application rate (Table 2). Compared to 0 Mg, the SOC concentrations were 17% and 25% greater in the 134 and 237 Mg treatments, respectively. Other studies conducted in semiarid climates have shown that soils receiving cattle manure can increase SOC (Chatterjee et al., 2017; Deng et al., 2006; Meek et al., 1982; Sommerfeldt et al., 1988). SOC is considered the leading baseline soil health indicator (Lehman et al., 2015) and manure addition is one of the few ways that SOC can be rapidly increased and potentially sustained in semiarid soils (Bierer, Leytem, Dungan, et al., 2021; Dungan et al., 2021; Ghimire et al., 2017) when compared to other management practices such as cover crop and

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TABLE 1 Selected soil health indicators (chemical and biological), their purpose, and potential implications when evaluating soil health effects of dairy manure applications to agricultural soils (adapted from Dungan et al. [2022]).

Method/indicator	Purpose	Implications for soil health and functions
Chemical		
pH; EC		Influences soil microbiome diversity and bacterial community composition
Nitrate (NO_3-N)	Direct measure of plant and microorganism available N	Dominate form of plant and microorganism available N and is a component of chlorophyll and ammino acids
Bicarbonate (Olsen) P	Indirect measure of plants and microorganism available P	Plays a role in energy transfer, photosynthesis, transformation of sugars and starches, nutrient movement, and transfer of genetic information
Soil organic C (SOC)	Indirect measure of Soil organic matter (SOM). SOC is 58% of SOM.	Main source of energy for soil microorganisms; indicator of C sequestration
Biological *β*-Glucosidase	Enzyme activity assay	Related to the C cycle, acting in the cleavage of cellobiose into glucose molecules. Because of its sensitivity, this enzyme is considered a soil quality indicator and is directly related to the quantity and quality of SOC.
β-Glucosaminidase	Enzyme activity assay	Catalyzes the hydrolysis of chitin to amino sugars (major source of mineralizable N). This hydrolysis is important in C and N cycling in soils
Phosphomonoesterase	Enzyme activity assay	Involved in soil P cycling. Catalyzes the hydrolyzes of organic P compounds to inorganic P compounds
Arylsulfatase	Enzyme activity assay	Involved in soil S cycling. Catalyzes the hydrolysis of ester sulfates. Highly correlated with SOC
Autoclaved citrate extractable protein	Amount of protein-like substances present in SOM	Major source of N that will become available to plants through mineralization; soil structure.
Potentially mineralizable N	Capacity of microbial community to mineralize N in organic residues	Indicator of labile N and microbial activity for increasing plant available N
Denitrification enzyme activity	Capacity of microbial community to reduce nitrate to N gases under anaerobic conditions	Related to N dynamics and loss of plant available N
Potential ammonia oxidation	Capacity of microbial community to oxidize ammonium	Related to N dynamics and crop N supply.

no-tillage (Acosta-Martinez et al., 2011; Blanco-Canqui et al., 2013; Liebig et al., 2019). However, identifying best management practices to maximize C sequestration and maintain crop yields is difficult in semiarid agricultural soils, with a particular lack of knowledge of relationships between SOC stabilization mechanisms and different management practices (Garcia-Franco et al., 2018).

In the present study, Olsen P concentrations were found to be 71% greater in the 237 Mg treatment compared to the non-manured control (Table 2). However, the crops in all treatments had sufficient P according to crop recommendations (Brown et al., 2010; Moore et al., 2012; Robertson & Stark, 2003; Walsh et al., 2019). In a study conducted in southern Idaho, Baxter et al. (2023) determined that open-lot dairy manures collected from 2015 to 2020 contained 6 g P kg^{-1} on average (range = 4.5–7.8 g P kg^{-1}). Due to the immobile nature of P, it can accumulate in soils when manure P is applied at rates that exceed plant requirements, thus, P surpluses can be expected to persist for long periods of time (Leytem & Mutegi, 2019; Leytem et al., 2021). In contrast to soil P, pH, electrical conductivity (EC), and NO_3-N concentrations were not found to be significantly elevated in the manure-treated soils (Table 2). Studies in Idaho have shown that dairy manure generally does not increase soil pH due to the high buffer capacity of alkaline calcareous soils (Baxter et al., 2023; Dungan et al., 2022). With respect to EC, Bierer et al. (2023) found that EC increased due to recent manure applications, but in the present study, we found that after 11 years the EC of the manure treatments was similar to the non-manure treatment. Because the irrigation water (from the Snake River) used in this study is relatively low in salts, any salts added in manure will be leached over time. The lack of differences in NO_3-N concentrations between treatments was likely impacted by the annual commercial fertilizer applications (168 kg N ha^{-1}) in the previous 2 years (2018 and 2019).

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TABLE 2 Selected soil health indicators (chemical and biological) in soil depths (0–30 cm for chemical, and 0–15 and 15–30 cm for biological) in 2020 from study treatments.

Chemical properties[a]	**Soil depth (cm)**	**Treatment** **Mg dry manure** ha^{-1}	**SOC** (g kg^{-1})	**pH**	**EC** (µS cm^{-1})	NO_3**-N** (mg kg^{-1})	**Olsen P** (mg kg^{-1})
	0–30 cm	0	10.1c	8.06	372.6	11.3	25.0b
		134	11.8b	8.04	410.7	7.0	26.9b
		237	13.4a	8.05	440.7	26.3	85.9a
		ANOVA *p*-value	**0.009**	0.954	0.308	0.350	**0.008**
Enzyme activities[b]			***β*-Glucosidase**	***β*-Glucosaminidase**	**Phosphomonoesterase**	**Arylsulphatase**	**Geometric mean index**
			µg *p*-nitrophenol $\text{g}^{-1}\ \text{h}^{-1}$				
	0–15 cm	0	75.9c	6.8b	162.7b	14.3b	32.9b
		134	97.4b	11.8a	192.6a	20.3a	45.8a
		237	116.1a	12.8a	209.4a	23.9a	52.1a
		ANOVA *p*-value	**0.004**	**0.083**	**0.054**	**0.042**	**0.021**
	15–30 cm	0	91.8c	10.2c	178.6c	17.0b	40.8c
		134	112.3b	16.7b	198.6b	28.0a	56.8b
		237	135.5a	17.0a	247.0a	30.7a	64.5a
		ANOVA *p*-value	**0.023**	**0.051**	**0.004**	**0.004**	**0.007**
N-Related indicators[c]			**ACE** µg g^{-1}	**PMN** µg NH_4-N g^{-1} 7 day^{-1}	**DEA** µg N_2O-N $\text{g}^{-1}\ \text{h}^{-1}$	**PAO** µg NO_2-N $\text{g}^{-1}\ \text{h}^{-1}$	
	0–15 cm	0	2606c	14.8	34.9b	1.17	
		134	3152b	15.2	40.3b	1.38	
		237	3629a	13.8	61.3a	1.75	
		ANOVA *p*-value	**0.003**	0.765	**0.043**	0.101	
	15–30 cm	0	2517c	11.2b	33.2c	1.10b	
		134	3217b	10.1b	44.1b	1.25a	
		237	3821a	14.3a	57.5a	1.20a	
		ANOVA *p*-value	**0.001**	**0.097**	**0.001**	**0.069**	

Note: Analysis methods and references are listed in the table footnotes. Significance was determined at the 0.10 probability level (least significant difference). Significant ANOVA *p*-values are bolded. Within each analyte and soil depth, values with the same letter are not significantly different.

Abbreviation: ANOVA, analysis of vaiance.

[a] Analysis protocols: soil organic carbon (SOC) (Bierer, Leytem, Rogers, et al., 2021), pH (Gavlak et al., 2005), electrical conductivity (EC) (Rhoades, 1996), nitrate-N (NO_3-N) (Mulvaney, 1996), and plant available phosphorus (P) (Olsen, 1954).

[b] Analysis protocols: *β*-glucosidase, *β*-glucosaminidase, alkaline phosphomonoesterase, and arylsulfatase (Acosta-Martinez et al., 2018). The geometric mean index of all enzyme activities was calculated as: $\sqrt[4]{\text{glucosidase} \times \text{glucosaminidase} \times \text{alkaline phosphomonoesterase} \times \text{arylsulfatase}}$ (García-Ruiz et al., 2008).

[c] Analysis protocols: autoclaved citrate extractable (ACE) soil proteins (Wright & Upadhyaya, 1996), potentially mineralizable N (PMN) (Waring & Bremner, 1964), potential ammonia oxidation (PAO) (Schmidt & Belser, 1994), and denitrification enzyme assay (DEA) (Hunt et al., 2003; Tiedje, 1994).

3.2 | Enzyme activities

The manure treatments, 11 years since the last application, had a significant effect on all enzyme activities at 0–15 and 15–30 cm (Table 2). Compared to 0 Mg, *β*-glucosidase, *β*-glucosaminidase, phosphomonoesterase, and arylsulphatase activities (measured as µg *p*-nitrophenol $\text{g}^{-1}\ \text{h}^{-1}$) in the 134 and 237 Mg treatments were anywhere from 18% to 88% greater at 0–15 cm and 11% to 81% greater at 15–30 cm. The enzyme activities were positively correlated with manure application rate and tended to be slightly greater in the subsoil at 15–30 cm. These enzymes play roles in C, N, P, and S cycling in soil (Table 1). The geometric mean index of the enzyme activities can serve as an overall indicator of soil health (García-Ruiz et al., 2008). The geometric mean index further highlights the effects of manure treatments on individual enzyme activities at both depth increments (Table 1). Because most livestock manures are easily decomposed by soil microorganisms, increased enzyme activities can be expected, and they are often correlated with application rate and associated SOC levels (Acosta-Martinez et al., 2011; Deng et al., 2006;

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Hou et al., 2012; Khorsandi & Nourbakhsh, 2007). In the present study, enzyme activities were ranked in the following order based on sensitivity to the past manure applications: β-glucosaminidase > arylsulfatase > β-glucosidase > phosphomonoesterase. In the same soil type, Dungan et al. (2022) found that in the year after the final dairy manure applications (annual and biennial over 7 years) that enzyme activities were greater overall and β-glucosidase was the most sensitive to manure, followed by β-glucosaminidase > phosphomonoesterase = arylsulfatase. The enzymatic differences between the present study and Dungan et al. (2022) suggest a change in the soil microbial community function and composition as time from the last manure application increases. However, the elevated enzyme activities in the present study do confirm a manure legacy effect of at least 11 years. Similarly, in a semiarid climate in Canada, legacy effects were still present at least 13 years after the last manure application, as determined by enzyme activities and microbial community composition (Lupwayi et al., 2019; Zhang et al., 2018).

3.3 | Nitrogen dynamics

Manures can contain significant amounts of needed microbial and plant available N, and the amounts of N can vary across animal types and diets (Pagliari et al., 2019). The manure from this study was from an intensively managed dairy system that implements feed supplementation for optimum milk production. Past manure treatments had a significant effect on all N-related indicators at 15–30 cm, but at 0–15 cm, only autoclaved citrate extractable (ACE) and denitrification enzyme assay (DEA) were significantly affected by manure (Table 2). In general, for all significant treatment/depth combinations, ACE, potentially mineralizable N (PMN), potential ammonia oxidation (PAO), and DEA for the 134 and 237 Mg treatments were greater than the 0Mg treatment for that depth. At 15–30 cm, ACE and DEA were 28%–73% greater in the 134 and 237 Mg treatments when compared to the non-manured control, while PMN was 28% greater in 237 Mg and PAO was 28% greater on average in both 134 and 237 Mg treatments. At 0–15 cm, ACE was 21%–39% greater in the 134 and 237 Mg treatments and DEA was 76% greater in the 237 Mg treatment compared to 0 Mg manure. The non-significant differences between treatments for PMN and PAO at 0–15 cm in the present study was likely due to equilibration. The purpose and function for each of these indicators can be found in Table 1. In brief, ACE represents a major organic N pool (i.e., protein) that will supply N to microbes and plants after mineralization, while PMN, PAO, and DEA represent the rate of N transformation during mineralization, nitrification, and denitrification, respectively. Both PMN and PAO supply crop N, but DEA represents a loss of plant available N. The application of livestock manure to soil has been shown to increase ACE concentrations, which in turn can help improve aggregate stability (Halder et al., 2021; Zhang et al., 2014). In a meta-analysis conducted by Mahal et al. (2018), it was reported that PMN was greater in soils receiving manure as opposed to inorganic N fertilizer or compost. Similarly, both PAO (Enwall et al., 2007; Nyberg et al., 2006; Tao et al., 2017) and DEA (Tenuta et al., 2000) rates were also found to be highly influenced by livestock manure fertilization. The influence of manure of ACE, PMN, PAO, and DEA was also verified by Dungan et al. (2022), but there is a scarcity of information regarding manure legacy effects on these biological indicators. The present study, however, provides new data showing that ACE, PMN, PAO, and DEA are effective at revealing past dairy manure applications in irrigated semiarid agricultural soils.

4 | CONCLUSIONS

Dairy manure has long-term effects on commonly used soil health indicators in southern Idaho semiarid irrigated soils. Dairy manure last applied 11 years prior to soil sampling in this study increased many of the measured soil health indicators. During the manure application period (2004–2009), the annual application rates (134 and 237 dry Mg ha^{-1}) were typical of general production practices. This was the first study to assess the effects of historic dairy manure applications on soil health indicators in the Northwest United States. These research findings will be combined with data from the USDA-ARS Dairy Agroecosystem Work Group Manure Priming and Manure Legacy projects to understand the long-term effects of dairy manure application on soil health, crop production nutrient cycling, and economics manure applications.

AUTHOR CONTRIBUTIONS

David D. Tarkalson: Conceptualization; data curation; formal analysis; investigation; project administration; writing—original draft. **Christopher W. Rogers**: Writing—review and editing. **Dave L. Bjorneberg**: Formal analysis; writing—review and editing. **Robert S. Dungan**: Formal analysis; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

The authors thank Sheryl Verwey and Chad McKinney for performing the soil healthy assays. Mention of trade names or commercial products in the publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. The USDA is an equal opportunity provider and employer.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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ORCID

David D. Tarkalson https://orcid.org/0000-0003-4670-1868
Christopher W. Rogers https://orcid.org/0000-0002-1989-1582

REFERENCES

Acosta-Martinez, V., Cano, A., & Johnson, J. (2018). Simultaneous determination of multiple soil enzyme activities for soil health-biogeochemical indices. *Applied Soil Ecology*, *126*, 121–128. https://doi.org/10.1016/j.apsoil.2017.11.024

Acosta-Martinez, V., Mikha, M. M., Sistani, K. R., Stahlman, P. W., Benjamin, J. G., Vigil, M. F., & Erickson, R. (2011). Multi-location study of soil enzyme activities as affected by types and rates of manure application and tillage practices. *Agriculture*, *1*, 4–21. https://doi.org/10.3390/agriculture1010004

Baxter, A. E., Leytem, A. B., Dungan, R. S., & Bjorneberg, D. (2023). Potential of winter double crops and tillage for managing manure-based nutrient loading. *Plant and Soil*. https://doi.org/10.1007/s11104-023-06072-w

Bierer, A., Dungan, R. S., Tarkalson, D. D., & Leytem, A. B. (2023). Fertilization strategy affects crop nutrient concentration and removal in semi-arid U.S. Northwest. *Agronomy Journal*, *115*, 351–369. https://doi.org/10.1002/agj2.21212

Bierer, A. M., Leytem, A. B., Dungan, R. S., Moore, A. D., & Bjorneberg, D. L. (2021). Soil organic carbon dynamics in semi-arid irrigated cropping systems. *Agronomy*, *11*, 484. https://doi.org/10.3390/agronomy11030484

Bierer, A. M., Leytem, A. B., Rogers, C. W., & Dungan, R. S. (2021). Evaluation of a microplate spectrophotometer for soil organic carbon determination in south-central Idaho. *Soil Science Society of America Journal*, *85*, 438–451. https://doi.org/10.1002/saj2.20165

Blanco-Canqui, H., Holman, J. D., Schlegel, A. J., Tatarko, J., & Shaver, T. M. (2013). Replacing fallow with cover crops in a semiarid soil: Effects on soil properties. *Soil Science Society of America Journal*, *77*, 1026–1034. https://doi.org/10.2136/sssaj2013.01.0006

Brown, B., Hart, J., Horneck, D., & Moore, A. (2010). *Nutrient management for field corn silage and grain*. University of Idaho Extension.

Chatterjee, A., Teboh, J., Nelson, S., Aberle, E., Schatz, B. G., & Zilahi-Sebess, S. (2017). Long-term effect of nitrogen and tillage management on soil carbon pools in the semiarid northern great plains. *Communications in Soil Science and Plant Analysis*, *48*, 730–740.

Deng, S. P., Parham, J. A., Hattey, J. A., & Babu, D. (2006). Animal manure and anhydrous ammonia amendment alter microbial carbon use efficiency, microbial biomass, and activities of dehydrogenase and amidohydrolases in semiarid agroecosystems. *Applied Soil Ecology*, *33*, 258–268. https://doi.org/10.1016/j.apsoil.2005.10.004

Dungan, R. S., Leytem, A. B., Moore, A. D., Bjorneberg, D. L., Grace, P. R., Brunk, C., & Rowlings, D. W. (2023). Growing and non-growing season nitrous oxide emissions from a manured semiarid cropland soil under irrigation. *Agriculture, Ecosystems & Environment*, *348*, 108413.

Dungan, R. S., Leytem, A. B., & Tarkalson, D. D. (2021). Greenhouse gas emissions from an irrigated cropping rotation with dairy manure utilization in a semiarid climate. *Agronomy Journal*, *113*, 1222–1237. https://doi.org/10.1002/agj2.20599

Dungan, R. S., Mckinney, C. W., Acosta-Martinez, V., & Leytem, A. B. (2022). Response of soil health indicators to long-term dairy manure in a semiarid irrigated cropping system. *Soil Science Society of America Journal*, *86*, 1597–1610. https://doi.org/10.1002/saj2.20462

Elzobair, K. A., Stromberger, M. E., Ippolito, J. A., & Lentz, R. D. (2016). Contrasting effects of biochar versus manure on soil microbial communities and enzyme activities in an Aridisol. *Chemosphere*, *142*, 145–152. https://doi.org/10.1016/j.chemosphere.2015.06.044

Enwall, K., Nyberg, K., Bertilsson, S., Cederlund, H., Stenström, J., & Hallin, S. (2007). Long-term impact of fertilization on activity and composition of bacterial communities and metabolic guilds in agricultural soil. *Soil Biology and Biochemistry*, *39*, 106–115. https://doi.org/10.1016/j.soilbio.2006.06.015

Garcia-Franco, N., Hobley, E., Hübner, R., & Wiesmeier, M. (2018). *Climate-smart soil management in semiarid regions. Soil management and climate change*. Elsevier.

García-Ruiz, R., Ochoa, V., Hinojosa, M. B., & Carreira, J. A. (2008). Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems. *Soil Biology and Biochemistry*, *40*, 2137–2145. https://doi.org/10.1016/j.soilbio.2008.03.023

Gavlak, R. G., Horneck, D. A., & Miller, R. O. (2005). *Soil, plant, and water reference methods for the Western Region*. WCC-103 Publication.

Ghimire, R., Norton, U., Bista, P., Obour, A. K., & Norton, J. B. (2017). Soil organic matter, greenhouse gases and net global warming potential of irrigated conventional, reduced-tillage and organic cropping systems. *Nutrient Cycling in Agroecosystems*, *107*, 49–62. https://doi.org/10.1007/s10705-016-9811-0

Halder, M., Liu, S., Zhang, Z. B., Guo, Z. C., & Peng, X. H. (2021). Effects of residue stoichiometric, biochemical and C functional features on soil aggregation during decomposition of eleven organic residues. *Catena*, *202*, 105288. https://doi.org/10.1016/j.catena.2021.105288

He, Z., Pagliari, P. H., & Waldrip, H. M. (2016). Applied and environmental chemistry of animal manure: A review. *Pedosphere*, *26*, 779–816. https://doi.org/10.1016/S1002-0160(15)60087-X

Hou, X., Wang, X., Li, R., Jia, Z., Liang, L., Wang, J., Nie, J., Chen, X., & Wang, Z. (2012). Effects of different manure application rates on soil properties, nutrient use, and crop yield during dryland maize farming. *Soil Research*, *50*, 507–514. https://doi.org/10.1071/SR11339

Hunt, P. G., Matheny, T. A., & Szögi, A. A. (2003). Denitrification in constructed wetlands used for treatment of swine wastewater. *Journal of Environmental Quality*, *32*, 727–735. https://doi.org/10.2134/jeq2003.7270

Indraratne, S. P., Hao, X., Chang, C., & Godlinski, F. (2009). Rate of soil recovery following termination of long-term cattle manure applications. *Geoderma*, *150*, 415–423. https://doi.org/10.1016/j.geoderma.2009.03.002

Khorsandi, N., & Nourbakhsh, F. (2007). Effect of amendment of manure and corn residues on soil N mineralization and enzyme activity. *Agronomy for Sustainable Development*, *27*, 139–143. https://doi.org/10.1051/agro:2007001

Larney, F. J., Li, L., Janzen, H. H., Angers, D. A., & Olson, B. M. (2016). Soil quality attributes, soil resilience, and legacy effects following

24719625, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/ael2.20128 by National Agriculture Library, Wiley Online Library on [29/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

topsoil removal and one-time amendments. *Canadian Journal of Soil Science*, *96*, 177–190. https://doi.org/10.1139/cjss-2015-0089

Lehman, R., Cambardella, C., Stott, D., Acosta-Martinez, V., Manter, D., Buyer, J., Maul, J., Smith, J., Collins, H., Halvorson, J., Kremer, R., Lundgren, J., Ducey, T., Jin, V., & Karlen, D. (2015). Understanding and enhancing soil biological health: The solution for reversing soil degradation. *Sustainability*, *7*, 988–1027. https://doi.org/10.3390/su7010988

Leytem, A., & Mutegi, J. (2019). Manure phosphorus management from a global perspective. *Better Crops Plant Food*, *103*, 26–28. https://doi.org/10.24047/BC103126

Leytem, A. B., Williams, P., Zuidema, S., Martinez, A., Chong, Y. L., Vincent, A., Vincent, A., Cronan, D., Kliskey, A., Wulfhorst, J. D., Alessa, L., & Bjorneberg, D. (2021). Cycling phosphorus and nitrogen through cropping systems in an intensive dairy production region. *Agronomy*, *11*, 1005. https://doi.org/10.3390/agronomy11051005

Liebig, M., Archer, D., Halvorson, J., Johnson, H., Saliendra, N., Gross, J., & Tanaka, D. (2019). Net global warming potential of spring wheat cropping systems in a semiarid region. *Land*, *8*, 32. https://doi.org/10.3390/land8020032

Lupwayi, N. Z., Zhang, Y., Hao, X., Thomas, B. W., Eastman, A. H., & Schwinghamer, T. D. (2019). Linking soil microbial biomass and enzyme activities to long-term manure applications and their nonlinear legacy. *Pedobiologia*, *74*, 34–42. https://doi.org/10.1016/j.pedobi.2019.04.001

Mahal, N. K., Castellano, M. J., & Miguez, F. E. (2018). Conservation agriculture practices increase potentially mineralizable nitrogen: A meta-analysis. *Soil Science Society of America Journal*, *82*, 1270–1278. https://doi.org/10.2136/sssaj2017.07.0245

Mckinney, C. W., Dungan, R. S., Moore, A., & Leytem, A. B. (2018). Occurrence and abundance of antibiotic resistance genes in agricultural soil receiving dairy manure. *FEMS Microbiology Ecology*, *94*, fiy010. https://doi.org/10.1093/femsec/fiy010

Meek, B., Graham, L., & Donovan, T. (1982). Long-term effects of manure on soil nitrogen, phosphorus, potassium, sodium, organic matter, and water infiltration rate. *Soil Science Society of America Journal*, *46*, 1014–1019. https://doi.org/10.2136/sssaj1982.03615995004600050025x

Miner, G. L., Delgado, J. A., Ippolito, J. A., Stewart, C. E., Manter, D. K., Del Grosso, S. J., Floyd, B. A., & D'Adamo, R. E. (2020). Assessing manure and inorganic nitrogen fertilization impacts on soil health, crop productivity, and crop quality in a continuous maize agroecosystem. *Journal of Soil and Water Conservation*, *75*, 481–498. https://doi.org/10.2489/jswc.2020.00148

Moore, A., Carey, A., Hines, S., & Brown, B. (2012). Southern Idaho fertilizer guide: Dry beans (CIS 1189). University of Idaho Extension.

Mulvaney, R. L. (1996). Nitrogen—inorganic forms. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, & M. E. Sumner (Eds.), *Methods of soil analysis: Part 3 chemical methods* (Vol. 5, pp. 1123–1184). ASA, CSSA, and SSSA.

Nyberg, K., Schnürer, A., Sundh, I., Jarvis, Å., & Hallin, S. (2006). Ammonia-oxidizing communities in agricultural soil incubated with organic waste residues. *Biology and Fertility of Soils*, *42*, 315–323. https://doi.org/10.1007/s00374-005-0029-6

Olsen, S. R. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. USDA.

Pagliari, P. H., Wilson, M., Waldrip, H. M., & He, Z. (2019). Nitrogen and phosphorus characteristics of beef and dairy manure. In H. M. Waldrip, P. H. Pagliari, & Z. He (Eds.), *Animal manure: Production, characteristics, environmental concerns, and management* (pp. 45–62). ASA, CSSA, and SSSA.

Rhoades, J. (1996). Salinity: Electrical conductivity and total dissolved solids. In D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, & M. E. Sumner (Eds.), *Methods of soil analysis: Part 3 chemical methods* (pp. 417–435). ASA, CSSA, and SSSA.

Robbins, C. W., Freeborn, L. L., & Mackey, B. E. (1997). Improving exposed subsoils with fertilizers and crop rotations. *Soil Science Society of America Journal*, *61*, 1221–1225. https://doi.org/10.2136/sssaj1997.03615995006100040030x

Robertson, L. D., & Stark, J. C. (2003). Idaho spring barley production guide (Bulletin 742). University of Idaho Extension.

Schmidt, E., & Belser, L. (1994). Autotrophic nitrifying bacteria. In P. J. Bottomley, J. S. Angle, & R. W. Weaver (Eds.), *Methods of soil analysis, Part 2: Microbiological and biochemical properties* (pp. 159–177). ASA, CSSA, and SSSA.

Sommerfeldt, T. G., Chang, C., & Entz, T. (1988). Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. *Soil Science Society of America Journal*, *52*, 1668–1672. https://doi.org/10.2136/sssaj1988.03615995005200060030x

Stott, D. (2019). *Recommended soil health indicators and associated laboratory procedures* (Soil Health Technical Note No. 450-03). U.S. Department of Agriculture, Natural Resources Conservation Service.

Tao, R., Wakelin, S. A., Liang, Y., & Chu, G. (2017). Response of ammonia-oxidizing archaea and bacteria in calcareous soil to mineral and organic fertilizer application and their relative contribution to nitrification. *Soil Biology and Biochemistry*, *114*, 20–30. https://doi.org/10.1016/j.soilbio.2017.06.027

Tarkalson, D. D., Bjorneberg, D. L., & Lentz, R. D. (2018). Effects of manure history and nitrogen fertilizer rate on sugar beet production in the Northwest US. *Crop, Forage & Turfgrass Management*, *4*, 1–9.

Tenuta, M., Bergstrom, D. W., & Beauchamp, E. G. (2000). Denitrifying enzyme activity and carbon availability for denitrification following manure application. *Communications in Soil Science and Plant Analysis*, *31*, 861–876. https://doi.org/10.1080/00103620009370483

Tiedje, J. M. (1994). Denitrifiers. In P. J. Bottomley, J. S. Angle, & R. W. Weaver (Eds.), *Methods of soil analysis, Part 2: Microbiological and biochemical properties* (pp. 256–257). Soil Science Society of America Book Series. ASA, CSSA, and SSSA.

USDA-NASS. (2023). Quick stats. https://quickstats.nass.usda.gov/

Walsh, O. S., Tarkalson, D., Moore, A., Dean, G., Elison, D., Stark, J., Neher, O., & Brown, B. (2019). Southern Idaho fertilizer guide: Sugar beets (Bulletin 935). University of Idaho Extension.

Waring, S. A., & Bremner, J. M. (1964). Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. *Nature*, *201*, 951–952. https://doi.org/10.1038/201951a0

Wright, S. F., & Upadhyaya, A. (1996). Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. *Soil Science*, *161*, 575–586. https://doi.org/10.1097/00010694-199609000-00003

Zhang, X., Wu, X., Zhang, S., Xing, Y., Wang, R., & Liang, W. (2014). Organic amendment effects on aggregate-associated organic

24719625, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/ael2.20128 by National Agriculture Library, Wiley Online Library on [29/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

C, microbial biomass C and glomalin in agricultural soils. *Catena*, *123*, 188–194. https://doi.org/10.1016/j.catena.2014.08.011

Zhang, Y., Hao, X., Alexander, T. W., Thomas, B. W., Shi, X., & Lupwayi, N. Z. (2018). Long-term and legacy effects of manure application on soil microbial community composition. *Biology and Fertility of Soils*, *54*, 269–283. https://doi.org/10.1007/s00374-017-1257-2

How to cite this article: Tarkalson, D. D., Rogers, C. W., Bjorneberg, D. L., & Dungan, R. S. (2024). Soil health indicators reveal that past dairy manure applications create a legacy effect. *Agricultural & Environmental Letters*, *9,* e20128. https://doi.org/10.1002/ael2.20128

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