



# The search for relationships between soil health and ranch-level economic outcomes – A case study on California rangelands

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## On the Ground

- Conservation advisors often want to know about the economics/profitability of soil health practices in grazing systems; however, relationships between soil health management and economic outcomes are lacking in grazing systems.
- We present a recent case study of California rangelands to demonstrate the challenges associated with determining economics/profitability of soil health practices in grazing systems.
- We found online tools available for researchers and conservation advisors to better understand soil health and forage production changes over time, but better on-the-ground information is still needed to estimate economic outcomes.
- Conservation groups and government agencies can play a role in quantifying economic outcomes by recording and sharing types of livestock management, length of management, and pre- and post-management soil health data.

**Keywords:** economics, geospatial, NRCS, prescribed grazing, ranch, soil health.

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## Introduction

Grazing lands comprise >60% of the land used globally for agriculture.<sup>1</sup> These vast meadows and pastures support carbon sequestration along with a multitude of other ecosystem

services.<sup>2</sup> Soil conservation practices play an important role in preserving working ranches for future generations in the western United States. Many ecosystem goods and services from rangelands rely on soil health.<sup>3</sup> Soil health is a term used to describe the physical, chemical, and biological indicators that make up soil characteristics.<sup>4</sup> Grazing practices may affect soil health.<sup>5–7</sup> Grazing and range management influence herbaceous biomass and plant functional groups, which are important to the sustainability of stocking rates.<sup>8–12</sup>

The Natural Resources Conservation Service (NRCS) defines conservation practice standards, including prescribed grazing and brush management, for the purpose of supporting soil health and other conservation goals.<sup>13,14</sup> These practices may provide associated ecological and ranch-level economic benefits over time.<sup>15,16</sup> Prescribed grazing strategies involve altering the intensity, frequency, timing, and duration of grazing to achieve one or more of a defined set of specific goals.<sup>14</sup> For example, the objective under the NRCS prescribed grazing practice standard most directly related to soil health is “Reduce soil erosion and maintain or improve soil health.”<sup>14</sup> Brush management strategies aim to achieve desired plant communities based on specific objectives.<sup>13</sup> The objective under brush management most directly related to soil health is “Restore or release desired vegetative cover to protect soils, control erosion, reduce sediment, improve water quality, or enhance hydrology.”<sup>13</sup> These goals also potentially support more ecologically and economically resilient and sustainable grazing systems. Such efforts may be even more critical given current and future challenges associated with a changing climate.

Soil health is a crucial driver in any ecosystem. Examples of important soil properties are texture, nutrient content, and microbial activity. All are closely related to soil organic matter (OM)—an excellent indicator of soil health—as it contributes to each of these properties. Increases in OM can positively affect water holding capacity, biomass production, and soil nutrient cycling, and thereby better support the sustainability of agricultural systems.<sup>17</sup>

Technical service providers and conservation advisors that connect with range livestock producers about soil health conservation practices often look for the “economic argument” or the “bottom-line.” People may be more willing to adopt practices if they save money or increase profits. Conservation practices do not necessarily save people money, especially in the short term. A potential lack of return on the money and time invested may be a deterrent to adoption of conservation practices. Potential barriers to realizing a return on investment in conservation practices on rangelands include tight profit margins, high upfront costs, and economic benefits that occur only in the future.<sup>15,16,18</sup>

Researchers typically need two key pieces of information to evaluate economic outcomes such as changes in profit: 1) the relationship between the conservation management practice and the economic variable(s) of interest (e.g., forage production and/or forage quality) and 2) the rate at which this economic variable will change as the result of management (e.g., rate of forage production and/or rate of forage quality increase). Dyer et al.<sup>15</sup> examined the economic impact of soil health management and found the rate of change in forage gains (immediate or growing logarithmically or linearly over time) can mean the difference between economic gains vs. losses.

The relationship between soil health and grazing management can be difficult to quantify. This makes associations among soil health, grazing management practices, and economic outcomes challenging. Barriers include, but are not limited to, a lack of baseline reference information, lack of replication, soil sampling costs, proper soil sampling techniques, and ultimately obtaining accurate long-term data to estimate relationships across a very diverse rangeland landscape. Interacting relationships between physical, chemical, and biotic properties in soil and variable weather complicate the ability to make clear associations between soil health and management. In addition, a specific grazing management approach that works well in one climate and/or plant community may not work as well in another.<sup>19</sup>

Difficulty with quantifying the relationship between OM and grazing management contributes to the challenge of connecting grazing management to soil health.<sup>20,21</sup> Inconsistent results in experiments relating soil carbon to grazing may occur due to discrepancies in study design and sampling methods, variation in herbivore species, legacy effects from prior management, small- and large-scale plant community variation, data source, climate, and soil type.<sup>20,22,23</sup> Data are also often proprietary or private, or monitoring does not occur, meaning there are no data, or sampling does not occur over the interval of interest.

Understanding the economics in terms of rangeland management requires rangeland managers, conservationists, soil scientists, geo-spatial analysts, economists, and other researchers to each bring very different but essential information to the table (Table 1). We present a recent case study as an example of the typical search for data needed to quantify economic outcomes. In this case study we estimated ranch-level economic outcomes associated with soil health management practices for the Coast, San Joaquin Valley, and Sacramento

Valley regions of California. We used current publicly available geospatial resources, placing this study at the forefront of rangeland research. However, we failed to identify strong connections between soil health and profitability, potentially due to mismatches in the temporal and spatial scale of available data and difficulties with connecting management practices to soil health improvements. By presenting these common data gaps, we hope to cultivate future opportunities to work together toward a more complete picture of the economics of management and soil health improvements on rangelands.

## Estimating economic outcomes – A case study

### Study area

Private and publicly owned rangelands comprise approximately 38% (15.4 out of 40.5 million ha [38 out of 100 million acres]) of the land area in California,<sup>24,25</sup> and these rangelands help support many ecosystem services dependent on soil health. California’s 69,000 farms and ranches generated more than \$50 billion USD in annual gross revenue in 2019. Although this number varies, approximately 665,000 head of beef cattle and 570,000 sheep graze California rangelands each year.<sup>26</sup> This case study focuses on cattle production. Cattle and calves are ranked as the fifth largest revenue source (\$3.1 billion USD) as compared to other agricultural commodities in the state.<sup>27</sup> California is also the fourth largest cattle producing state in the country.<sup>28</sup>

These California rangelands support several ecosystem services including habitat and biodiversity.<sup>29,30</sup> Given past and anticipated changes in land use and impacts from climate change,<sup>31</sup> these lands serve an increasingly important role in California’s water supply.<sup>32</sup> Ecosystem services generated annually from rangelands and pastures supported by beef cattle ranches and farms in California are conservatively estimated to be \$873.7 million USD.<sup>33</sup>

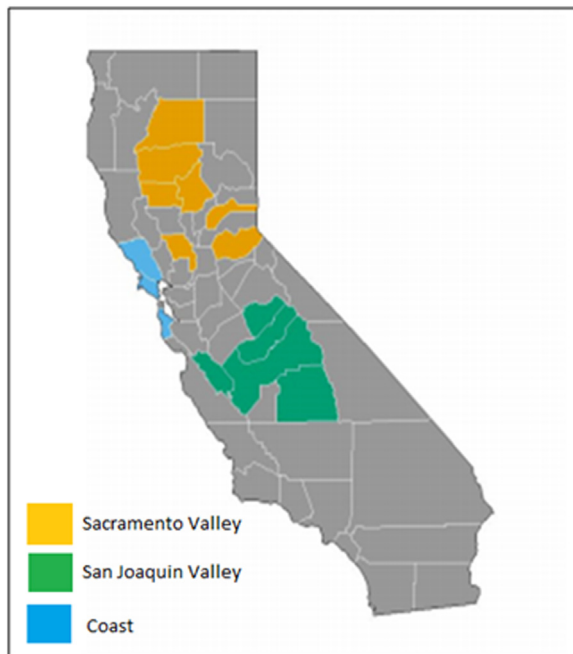
Our study area was entirely within the state of California located in the Mediterranean climate zone, where most of the livestock is produced.<sup>28,34</sup> This area is approximately within the California Subtropical Fruit, Truck, and Specialty Crop Region.<sup>35</sup> This region’s wide variety of crops and agricultural enterprises include beef cattle production on feedlots and rangelands. Federal land makes up about 16% of this region.<sup>35</sup> Very little rainfall occurs in this area from late in April through October.<sup>35</sup> The three subregions represented in this analysis were the Coast, San Joaquin Valley, and the Sacramento Valley (Fig. 1).

*Coast region*—The Coast region includes Major Land Resource Areas (MLRA) 14 (Central California Coastal Valleys) and 15 (Central California Coast Range).<sup>35</sup> Private farms and ranches constitute the primary land use in this region. The dominant soil orders in these MLRA’s are Alfisols, Entisols, Mollisols, and Vertisols. Most of the soils in the area have a thermic soil temperature regime, a xeric soil moisture

**Table 1**

Data needs and information gathering roles of various participants in conservation practices and economic analysis at the ranch-level

Data needs	Soil health management relationship to forage production	Forage production relationship to herd size and profitability
Information gathering roles	Conservation organizations work with ranchers and researchers to provide in the field data about specific management practices used and forage production changes over time. Geospatial data can identify trends or fill in data gaps.	Economists' model using representative ranches, enterprise budgets, and established ranch-level economic models and methods of analysis.



**Figure 1.** Study area: Coast (blue) – counties: Sonoma, Marin, and San Mateo, the San Joaquin Valley (green) – counties: San Benito, Fresno, Madera, Mariposa, and Tulare and the Sacramento Valley (orange) – counties: Yolo, El Dorado, Nevada, Butte, Glenn, Tehama, and Shasta.<sup>46</sup>

regime, and mixed or smectitic mineralogy. They generally are very shallow to very deep, somewhat excessively drained or well drained, and loamy or clayey. South of San Francisco the average annual precipitation is 150 mm to 510 mm (6-20 inches). North of San Francisco the average annual precipitation is 455 mm to 1,015 mm (18-40 inches). The average annual temperature is 10°C to 19°C (51-66°F), decreasing from south to north. The freeze-free period averages 275 days and ranges from 180 to 365 days, decreasing in length with elevation and from south to north. This area supports grasses, shrubs, and trees. Naturalized annual grasses and forbs are dominant in many areas. Soft chess (*Bromus hordeaceus* L.), wild oats (*Avena fatua* L.), bromes (*Bromus* spp.), fescues (*Festuca* spp.), filaree (*Erodium cicutarium* [L.] L'Hér. ex Aiton), burclover (*Medicago polymorpha* L.), and some remnant perennials are the major species.

*Sacramento Valley and San Joaquin Valleys*—Both Sacramento and San Joaquin Valleys lie within MLRA 017X.<sup>35</sup> Production of livestock on rangelands constitutes the main enterprise in these areas. Alfisols, Aridisols, Entisols, Mollisols, and

Vertisols comprise the dominant soil orders. A thermic soil temperature regime, an aridic or xeric soil moisture regime, and mixed or smectitic mineralogy are dominant in soils. They commonly are very deep, well drained or moderately well drained, and loamy or clayey. The San Joaquin Valley's average annual precipitation is 125 mm to 305 mm (5-12 inches). In most of the Sacramento Valley the average annual precipitation is 305 mm to 760 mm (12-30 inches). The Tulare Basin, at the southern end of this MLRA, typically receives less than 150 mm (6 inches) of rainfall annually. The average annual temperature 15°C to 19°C (59-67°F) decreases from south to north. The freeze-free period averages 325 days (80-365 days range), decreasing in length with elevation and from south to north. This area supports shrubs, trees, and naturalized annual grasses. The dominant species on grassland are soft chess, wild oats, filaree, burclover, ripgut brome (*Bromus diandrus* Roth), and foxtail fescue (*Vulpia myuros* [L.] C.C. Gmel.).

### Analysis of soil health, forage production, and management

Our primary goal was to better understand the dynamics among soil health, management practices, and forage production to estimate economic outcomes. With this goal in mind, we identified possible relationships among 1) precipitation and aboveground Annual Primary Productivity (APP),<sup>36-40</sup> which is the main component of any consumable forage calculation; 2) soil health and APP; and 3) soil health, APP, and management practices. We explain the problems we encountered in combining publicly available data with on-the-ground data as the study progressed. These problems resulted from lack of information at the appropriate scale because of considerable spatial variation in soil parameters, lack of information about management (what, when, where management occurred), and an insufficient number of years of soil health data points.

*Precipitation and annual primary productivity*—We estimated APP and the relationship between APP and precipitation over time within each region. We used satellite-derived estimated APP data available from the United States Department of Agriculture (USDA) Forest Service Rangeland Production Monitoring Service (RPMS) from 1984 to 2018 at a 250 m resolution (each pixel represents an area of 250 by 250 m on the ground [820 by 820 feet]).<sup>41,42</sup> RPMS approximated APP, which is typically greater than the amount consumed as forage, but it is an essential part of

the calculation for estimating forage production and it was the data we had available. APP based on the Normalized Difference Vegetative Index<sup>43</sup> is a widely accepted method to remotely determine vegetative production. APP data were extracted using the USDA Forest Service Rocky Mountain Research Station Raster Utility tool and averaged at the county level. Precipitation correlates most closely with and influences the Normalized Difference Vegetative Index.<sup>44</sup> We estimated precipitation at the county level using Oregon State University's Parameter-elevation Regressions on Independent Slopes Model (PRISM) derived data. To get annual data, we summed monthly PRISM data,<sup>45</sup> provided from 1981 to 2019 and reported in millimeters and averaged by counties within our study area. After we gathered the data, we performed a regression analysis (Appendix, Eq. A.1; Table A.1) between precipitation for matching years for 1984 to 2018 to estimate relationships and the average APP for the regions.

*Soil health and annual primary productivity*—We determined which of several soil characteristics were associated with changes in APP. Our first step was to gather data from the Point Blue Conservation Science's Rangeland Monitoring Network (RMN), which provided a regional dataset for 2016 to 2017.<sup>46</sup> Unfortunately, Point Blue Conservation Science could not provide the second sampling year of RMN data as originally planned. We shifted our research methods and analyses and employed a second set of data for comparison from the NRCS Web Soil Survey (WSS) website database.<sup>47</sup> This database provided OM, bulk density, texture data, and rangeland forage production data for 2019 in each county in the three regions for the same soil types given in the RMN data.

We performed two different regression analyses: one using the RMN data and one using the WSS soil health data (Appendix, Eq. A.2-A.3; Table A.2-A.3). Ultimately, we concluded that it was difficult to determine any outcomes or relationships using either data source. We obtained mixed results and a low R square value for the WSS analysis indicating little relationship between variables. There is also previous literature indicating potential difficulties in using WSS's soil data estimates.<sup>21</sup> In addition, caution should be taken when drawing conclusions or determining relationships based on 1 year of soil data from any source (field sampled or web-based). We also found a negative correlation to APP (Table A.3) that was counter intuitive. These relationships are outweighed by bulk density and location.

*Soil health, annual primary productivity, and management practices*—In our final step, we estimated potential relationships between soil health, APP, and management practices. The final regression analysis incorporated management practice information (prescribed grazing or brush management), RPMS APP data, RMN soil data, and PRISM data (precipitation; Appendix Eq. A.4; Table A.4). We used brush man-

agement<sup>13</sup> and prescribed grazing<sup>14</sup> information, as we estimated these to be the most relevant USDA-NRCS practices for the study area that could affect APP and soil organic carbon. We obtained the practice data from the years 2005 to 2019, including the number of hectares in each county where that practice was implemented (R. Gillaspay, NRCS, pers. comm.).

Ultimately, we could only conclude that an increase in APP over 35 years occurred and may be the result of management; however, our analysis of the soils data did not detect this. That is, information needs remain for the economic analysis. We identified economic outcomes based on if increased APP is from management (see the Representative ranch economic outcomes section). From the data available we determined there was an average increase of 14.7 kg/ha (13.2 lb/acre) in APP as a factor of location, time, and precipitation for the regions of Sacramento Valley and San Joaquin Valley. This relationship was the best we could estimate for APP over time as the result of management. The estimated increases in APP over time in each region (Table A.5) were used to estimate forage inputs in the economic model (see Representative ranch economic outcomes section). We conducted an economic analysis (see next section), but it is based on the potential value of management outcomes where the increase in APP was from management. However, we cannot state the likelihood that or what portion of this value is from management versus other factors (e.g., precipitation).

## Representative ranch enterprise production data

We used enterprise production data to further formulate representative ranch operations for each region. Enterprise budgets capture potential regional differences, such as forage and feed calendars. University of California Davis Extension Enterprise Budgets showed representative ranches for each region had key differences in seasonal forage availability and constraints and other key parameter values (Tables 2, 3, and 4).<sup>48-51</sup> It is important to model these regions separately as regional factors can influence economic outcomes from investment in conservation practices. Cost data were adjusted for inflation using values from the USDA National Agriculture Statistic Service (NASS) dataset.<sup>52</sup>

## Representative ranch economic outcomes

We employed the Recursive Multi-Period Linear Programming conceptual model adapted from Torell et al.<sup>53</sup> to estimate economic impacts for each representative ranch in each region. These models have been used in several past studies to estimate the ranch-level economic impacts of various management or policy changes. Topics of past studies included greater sage-grouse (*Centrocercus urophasianus*) management on western rangelands,<sup>54</sup> off-stream water developments for cattle to improve riparian health,<sup>55</sup> altering land use and environmental policies for rangeland users,<sup>56</sup>

**Table 2**Representative ranch grazing on and off dates used in economic models shown according to land type for each study area in California<sup>48-50</sup>

Region	Land Type	1 February to 31 March	1 Apr to 30 April	1 May to 31 May	1 June to 31 August	1 September to 31 October	1 November to 31 January
Coast	Deeded	x	x	x	x	x	x
	Irrigated Pasture			x	x	x	
	Alfalfa Hay	x	x	x	x	x	x
Sacramento Valley	Deeded	x	x	x	x	x	x
	Irrigated Pasture			x	x	x	
	Alfalfa Hay	x	x	x	x	x	x
San Joaquin Valley	Deeded	x	x	x	x	x	x
	Irrigated Pasture			x	x	x	
	Alfalfa Hay	x	x	x	x	x	x

Note. Study area: Coast Region – counties: Sonoma, Marin, and San Mateo, the San Joaquin Valley Region – counties: San Benito, Fresno, Madera, Mariposa, and Tulare and the Sacramento Valley Region – counties: Yolo, El Dorado, Nevada, Butte, Glenn, Tehama, and Shasta.

**Table 3**Representative ranch parameters used in economic models for each study area in California<sup>48-50</sup>

Model parameter	Coast	Sacramento Valley	San Joaquin Valley
Initial herd size	300	300	300
Calf crop percentage at birth	95%	89%	89%
Minimum cow replacement rate	10%	12%	13%
Bull replacement rate	25%	25%	30%
Percentage of heifer calves kept	42%	80%	80%
Cow to bull ratio	20 to 1	20 to 1	20 to 1
Fixed ranch expenses (USD)	\$48,252	\$50,594	\$50,071

Note. Study area: Coast Region – counties: Sonoma, Marin, and San Mateo, the San Joaquin Valley Region – counties: San Benito, Fresno, Madera, Mariposa, and Tulare and the Sacramento Valley Region – counties: Yolo, El Dorado, Nevada, Butte, Glenn, Tehama, and Shasta.

**Table 4**Representative ranches land types and costs per unit used in economic models for each study region in California<sup>48-50</sup>

Region	Land type	Units	Number of units	Cost per unit (USD)
Coast	Deeded	ha	1,600	\$17.83
	Irrigated pasture	ha	1,010	\$23.00
	Alfalfa hay	kg	54,430	\$190.00
Sacramento Valley	Deeded	ha	2,460	\$17.83
	Irrigated pasture	ha	1,160	\$30.00
	Alfalfa hay	kg	54,430	\$160.00
San Joaquin Valley	Deeded	ha	2,460	\$17.83
	Irrigated pasture	ha	1,215	\$21.60
	Alfalfa hay	kg	81,650	\$180.00

Note. Study area: Coast Region – counties: Sonoma, Marin, and San Mateo, the San Joaquin Valley Region – counties: San Benito, Fresno, Madera, Mariposa, and Tulare and the Sacramento Valley Region – counties: Yolo, El Dorado, Nevada, Butte, Glenn, Tehama, and Shasta.

western juniper control,<sup>57</sup> grazing distribution treatments,<sup>58</sup> and cheatgrass invasion.<sup>59</sup>

We used these models to estimate economic outcomes by incorporating estimated increases in APP (Net Present Value of the net income stream over a 35-year planning horizon) using 100 simulated cattle price iterations. These price iterations came from Nevada and California regional prices reported by CattleFax, stochastically selected from price variations between 1980 and 2012.<sup>54</sup> Model solutions were obtained using the Generalized Algebraic Modeling System with the MINOS solver.<sup>60</sup> We assumed only a portion of the estimated APP (Table A.4) to be considered as forage in the model. We used the NRCS standard of 50% of the APP to be used by cattle (i.e., harvest efficiency), of which 25% of forage was assumed to be consumed and 25% was assumed to be destroyed.<sup>61</sup>

We estimated economic benefits for each region's representative ranches for engaging in soil health practices, given the assumption that the production increases came from these practices (Table 5). Note these estimates did not include the cost of implementing the practice. This gives an estimate of gross benefits but does not include management costs. Dyer et al.<sup>15</sup> estimated management costs for a representative ranch in Wyoming in a sagebrush steppe plant community, considering rotational grazing as the soil health practice of interest. Costs estimated in the Dyer et al.<sup>15</sup> study may be considerably different given the cost of living and other factors that may increase the cost of goods and services in California. These are also different plant communities and climates; therefore, specific practice approaches may need to be different to attain benefits. However, if implementation costs in Wyoming do provide a good estimate for California, then there would be an estimated positive net benefit (in addition to a gross benefit) in improving soil health as well for all three regions (Table 6). Van Liew et al.<sup>62</sup> could be used to compare modeled practice benefits from this study to prescribed brush management costs. The same caveats relating to different practice approaches for different plant communities and geographically specific equipment costs apply to this transference. Also, costs would need adjustment to account for inflation.

**Table 5**

Estimated increases in forage production from soil health improvements for each region were used to find estimated average increases in the representative ranches NPV of the net income stream, average increase in gross annual sales, and average increase in annual herd size (brood cows) over a 35-year time horizon

Region	Change in NPV	Change in annual gross sales	Original herd size	Change in herd size
Coast	\$311,729	\$27,705	300	+23
Sacramento Valley	\$480,225	\$39,443	300	+35
San Joaquin Valley	\$428,055	\$37,845	300	+36

*Note.* Study area: Coast Region – counties: Sonoma, Marin, and San Mateo, the San Joaquin Valley Region – counties: San Benito, Fresno, Madera, Mariposa, and Tulare and the Sacramento Valley Region – counties: Yolo, El Dorado, Nevada, Butte, Glenn, Tehama, and Shasta.  
NPV, Net Present Value.

**Table 6**

Estimated NPV of the net benefit calculated as the NPV of estimated gross benefits in the California case study minus the present value of management costs as estimated in Dyer et al.<sup>15</sup>

Region	Estimated gross benefits	Estimated NPV of practice cost from Dyer et al. <sup>15</sup>	Estimated NPV of net benefit
Coast	\$311,729	\$170,890	\$140,839
Sacramento Valley	\$480,225	\$170,890	\$309,335
San Joaquin Valley	\$428,055	\$170,890	\$257,166

*Note.* Study area: Coast (blue) – counties: Sonoma, Marin, and San Mateo, the San Joaquin Valley (green) – counties: San Benito, Fresno, Madera, Mariposa, and Tulare and the Sacramento Valley (orange) – counties: Yolo, El Dorado, Nevada, Butte, Glenn, Tehama, and Shasta.  
NPV, Net Present Value.

## Discussion

Our case study followed the typical process that natural resource/agricultural economists pursue in developing and parameterizing bioeconomic models. We determined primary affected actors, affecting actors, and the economic variable(s) of interest. We also sought to find the relationships between these variables (e.g., how soil health improvements through brush management and prescribed grazing affect forage production). We brought together several sources to inform potential relationships between soil health, management, and forage production (i.e., the main economic variable of interest in this setting) and therefore the relationship between soil health improvements and profitability.

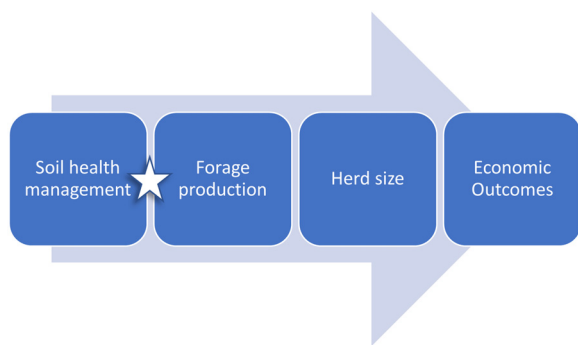
Our study provides an example of the challenges of interpreting scientific data that vary greatly in terms of quality and consistency of collection. To connect management practices with economic outcomes we ideally would use multiple years of soil health data, as changes take time. We also ideally would have known the specific grazing management practices that occurred and the locations. Point Blue Conservation Science's agreement with the landowners made specific locations proprietary. Furthermore, we only had access to 1 year of data.

While soil health management practices may have resulted in an increase in forage over 35 years, we did not detect this relationship in the soils data. This increase in forage could be associated with many possible factors. For example, changes in management and more conscious grazing management practices may help to better protect ecosystem services.<sup>63</sup> Avoiding improper grazing and improving ground cover can benefit

both the soil and vegetation.<sup>14</sup> Climate change may increase forage productivity due to more mild winters and higher average rain,<sup>64</sup> which could explain increases in forage production over time, though more analysis would be needed to make this conclusion. However, results may be temporary due to projected increases in heat stress, water deficits, and other factors.<sup>64</sup> Furthermore, we see several possible reasons that could explain why we found no relationship between soil health and production. These reasons include lack of data, source of data, and data from only one point in time. Difficulty with quantifying these relationships is common in soil health research. Multiple studies have shown a neutral response of soils relative to management.<sup>22,65,66</sup> Therefore, usually it is difficult to know the degree to which management practices contributed.

Specifics related to WSS data may also explain why relationships between soil health and production were not found. Gergeni and Scasta<sup>21</sup> found no correlation between WSS %OM estimates and field-derived %OM values in their cold arid steppe study sites. They also found %OM values to be consistently higher in the field than in WSS estimates. For this reason, they recommended managers conduct their own soil sampling to develop baselines and compare those to WSS estimates. They also encouraged managers to conduct soil samples over time to determine if changes in rangeland soil health occurred. WSS could add more data and more field verification to benefit data users.

While Dyer et al.<sup>15</sup> pertained to a different plant community and climate, it did not have the necessary information to estimate the relationship between soil health practices and forage production. Dyer et al.<sup>15</sup> took a “what if” approach



**Figure 2.** Researchers understand the relationship between forage production, herd size, and economic outcomes (profit). However, biophysical interactions, different scales of available data, and the desire for management privacy on private grazing lands make it difficult to quantify the relationship between soil health and forage production over time (star).

that explored potential differences in profitability from management given different rates of forage production increases. They compared outcomes given an immediate increase versus an increase over time at a fast (linear) or slow (logistic) rate of increase. It was estimated that an immediate increase in forage production provided a positive net benefit, but linear and logistic increases provide a negative net benefit (i.e., implementation costs were higher than the increase in the gross Net Present Value of the income stream).

Our study aimed to go a step beyond theoretical relationships in the hopes of making stronger connections between soil health and profitability. We found a significant relationship between forage production and time using real, state-of-the-art data in areas under management. But this is not enough for researchers to say these changes in forage production came from improving soil health through management. Once again, we have to assume these relationships.

This California case study provides one example of the common struggle of interdisciplinary teams to make the connections between hard scientific data and profit. The work of researchers, conservation groups, land managers, and others can play an important role in understanding “the economics.” Economists have a good understanding of the relationship between key economic variables (e.g., forage production) and profit outcomes (e.g., ranch-level economics). They need, however, a better understanding of the relationship between management (e.g., soil health improvement practices) and the key economic variable (e.g., forage production) for defensible connections (Fig. 2). The “key economic variable” in this case study was forage production but can be more generally thought of as a variable or indicator that is measurable and connects ecological changes to changes in human wellbeing.<sup>67</sup>

Moving into the future, relating changes in variability rather than average changes in forage production to management may be increasingly important. What happens to the variability of production may be most relevant to profitability,<sup>68</sup> especially for operations that cannot easily adjust forage demand without sell-offs resulting in considerable economic

cost. Amongst other factors affecting forage production variability and profitability in a changing climate, the projected expansion of heat- and drought-tolerant naturalized annual grasses raises concern about limited forage production during periods of drought as compared with perennial grasses.<sup>64,69</sup> The proliferation of these invasive annual grasses may also have an impact on soil health. Future work might analyze production factors more specific to annual grasses if relevant. For example, in the Mediterranean climate of California, growing season is thought to be the primary driver of annual grassland forage production,<sup>69</sup> although residual dry matter may also be important as a common determinant of proper grazing levels.<sup>26</sup>

To better inform economic outcomes, conservation groups and government agencies (e.g., NRCS) can provide conservation practice information, including length of practice, type of practice, and on the ground soil health data at more local levels (e.g., county level). This can help align spatial and temporal scales of data to make informative associations between practices, publicly available forage production data, and economic outcomes. We fully recognize the limitations of this case study that resulted from the lack of data and information pulled from disparate sources. Nevertheless, the results demonstrate the important economic effects that focusing on soil health and cattle management might have on ranches.

Our case study highlights the types of information and the scales at which information is needed over long time periods, which is our primary outcome. Even 2 years of soil health data is rarely sufficient. To show differences in soil health, practices, and related forage production, data collection points ideally would be over multiple years. Hence, researchers need data near the start of the change in practices being examined and data collected over decades afterwards. Research would also benefit from more frequent data collection. Another option would be a cross-sectional study to see if past management can be quantified. For example, if ranches within one region (e.g., MLRA, ecoregions) could be surveyed for soil properties, types of management practices applied, length of management, and production, it could help to tease out relationships across broad areas. This would take unprecedented public and private cooperation and extensive data collection with concomitant costs.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rala.2023.03.004.

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