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RESEARCH ARTICLE

The potential of regenerative agriculture to improve soil health on Gotland, Sweden

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Abstract

Background: Regenerative agriculture has gained attention in mainstream media, academic literature, and international politics in recent years. While many practices and outcomes relate to RA, there is no uniform definition of the term, and only a few comprehensive scientific studies exist of "real-life" farms and the complexity of what is considered regenerative management and its impact on soil health.

Aims: This study aimed to relate the impact of single and various combinations of regenerative management practices to soil health indicators on Gotland, Sweden.

Methods: Soil health of 17 farm fields and six gardens was assessed on 11 farms that had applied regenerative agricultural practices for zero to 30 years. We measured a variety of physical (bulk density, infiltration rate, wet aggregate stability, root depth and abundance, penetration resistance), chemical (pH, electric conductivity, C:N ratio, total organic carbon) and biological (earthworm abundance, active carbon, microbial biomass carbon) soil indicators. These parameters were related to regenerative practices (reduced tillage, application of organic matter, livestock integration, crop diversity, and share of legumes and perennials) through a combination of hierarchical clustering, Analysis of Variance and Tukey's tests, principal component analysis, and multiple linear regressions.

Results: At our study sites, the application of organic matter had a positive impact on bulk density, carbon-related parameters, wet aggregate stability, and infiltration rate, while reduced tillage and increased share of perennials combined had a positive impact on vegetation density, root abundance and depth, and wet aggregate stability. The field plots were divided into four clusters according to their management, and we found significantly higher values of total organic carbon (*), C:N (*), infiltration rate (**), and earthworm abundance (*) for *crop-high-org-input*, the management cluster with highest values of organic matter application and no tillage. We found significantly higher values of vegetation density (***) and root abundance (**) for *perm-cover-livestock*, the cluster with no tillage, integration of livestocks, and permanent cover (*** $p < 0.001$, ** $p < 0.01$, *$p < 0.05$, °$p < 0.1$).

Conclusions: We support existing knowledge on positive impacts of regenerative practices, namely, the addition of organic amendment that improved carbon-related parameters, as well as the positive effects on soil structure of reduced tillage in combination with an increased share of perennials. We argue for an outcome-based, and principle-led concept of regenerative agriculture as a context-dependent agricultural approach.

KEYWORDS
carbon sequestration, organic amendments, reduced tillage, soil fertility, soil organic carbon

1 | INTRODUCTION

An increasing popularity of regenerative agriculture (RA) is following a surge in climate change (CC) awareness. Regenerative agriculture has a core focus on restoring soil health with the co-benefit of CC mitigation through soil carbon (C) sequestration. It has gained political attention and was listed as a "sustainable land management practice (IPCC, 2020)" in IPCC's special report on Climate Change and Land in 2019. According to the EU's New Soil Strategy (European Commisssion, 2021a, 2021b, 2021c, 2021d), sustainable soil management is to be the "new normal," and a set of sustainable soil management practices should be prepared and adapted to different ecosystems under the strategy.

In a recent report, the IPCC (2021) states that global warming of 1.5°C relative to 1850–1900 is expected to be exceeded during the 21st century, increasing the frequency and intensity of heavy precipitation and flooding together with an increased frequency of severe droughts with adverse impacts on food security and terrestrial ecosystems.

The land is simultaneously a source and a sink of carbon dioxide (CO_2), methane, and nitrous oxide (N_2O) and plays a key role in the greenhouse gas (GHG) exchange with the atmosphere (IPCC, 2020). Emissions from agriculture and expansion of agricultural land represent 16%–27% of total anthropogenic emissions (IPCC, 2020).

Land conversion, land-use intensification, and unsustainable farming practices have contributed to widespread land degradation (e.g., Gibbs & Salmon, 2015; IPCC, 2020; Singh et al., 2018; Yang et al., 2020). This leads to the risk of exceeding the soil's capacity to withstand predicted climate disturbances (IPCC, 2020), which is a dire situation given that healthy soils are the foundation of our food production. Agriculture also faces the challenge of rising food demand caused by population and income growth (IPCC, 2020; Olson et al., 2016). Accordingly, solutions include increased food production either within or beyond the current agricultural land (Giller et al., 2021). Expansion of cultivated land and related conversion of natural ecosystems involves the inclusion of less productive land currently functioning as C sinks and would lead to further land degradation, habitat loss, and alteration of biogeochemical and hydrological cycles (Williams et al., 2021).

Instead, using the potential of managed soils to restore soil organic carbon (SOC) and soil productivity by improved management practices (Singh et al., 2018) and enhancing existing croplands can facilitate active C storage and prevent C loss from newly converted agricultural soils, habitat conversion and biodiversity loss (Bossio et al., 2020). Soil health as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans (Natural Resources Conservation Service, 2012)" is key for local and global food security, and SOC is a central factor for sustainable maintenance of soil health (Ramesh et al., 2019). Bossio et al. (2020) call soil organic matter (SOM)-enhancing opportunities "no-regrets opportunities," as they have a variety of positive outcomes on different environmental and social levels without related trade-offs. An increase in SOM will positively affect soil properties such as nutrient supply, soil structure, water holding capacity, and microbial life (Johnston et al., 2009; Watts & Dexter, 1997), leading to increased fertility and CC resilience, and reduced erosion. The storage capacity of SOC depends largely on climate, topography, and soil characteristics like texture, C:N ratio of SOM, specific surface area of soil particles, biological composition of SOC, and soil microorganisms (Ussiri & Lal, 2017). A basic strategy for terrestrial C sequestration for CC mitigation in agriculture consists of (1) increasing C inputs and (2) maximizing the mean residence time of C in the soil (Lal et al., 2018). A new equilibrium at high SOC levels can be reached after about 30–70 years in warm temperate regions (Han et al., 2016), where fertile soils may be closer to the C saturation potential than largely degraded soils in the same climate (Six et al., 2002).

Contemporary academic literature (Burgess et al., 2019; Giller et al., 2021; Lal, 2020; Newton et al., 2020; Schreefel et al., 2020) acknowledges that there is no uniform definition of RA and no regulatory framework for it. Thus, the need for a clear definition of the term for any given use and context is highlighted (Giller et al., 2021; Newton et al., 2020).

Here, we define RA as an ever-developing, complex, and context-dependent agricultural approach aiming to restore and regenerate degraded land and contribute to CC adaptation with mitigation co-benefits. In RA, the soil is the entry point to rethink food systems with the aim of enhancing biological, physical, chemical, as well as cultural ecosystem services in response to ecological conditions and the climate crisis, on a local as well as a global level.

Key practices incorporated by current definitions of RA include the addition of organic matter (OM) through manure, compost, green manures, and so forth, reduced or no tillage, ley crops, cover crops or other permanent soil cover, and crop-livestock integration (Elevitch et al., 2018; Newton et al., 2020). Other, less mentioned practices, are diverse crop rotations, perennial cropping systems, agroforestry and tree crops, maintenance of living roots in the soil, residue management, addition of biochar and reduced external inputs (EASAC, 2022; Giller et al., 2021; Lal, 2020; Schreefel et al., 2020).

Anticipated outcomes of RA may be C sequestration and enhanced soil fertility, biodiversity, and climate resiliency. Co-benefits may be improved watersheds and closed nutrient loops, reduced GHG emissions, same or higher farm productivity, and improved animal welfare, rural livelihoods, food access, and nutritional quality (Al-Kaisi & Lal, 2020; Elevitch et al., 2018; Giller et al., 2021; Newton et al., 2020; Rodale Institute, 2014). For example, less mineral fertilization through improved crop rotations and nutrient recycling may lead to lower N_2O emissions. Potential trade-offs are increased N_2O emissions through increased C storage, higher demand for weed management caused by, for example, reduced tillage intensity, and a risk of lower food production by the prioritization of non-crop structures to enhance biodiversity (EASAC, 2022).

SOC and soil health are closely related and their depletion often happens concurrently (Lal, 2004). It is expectd that SOC stocks vary between associated management practices, for example, higher SOC stocks on fields with livestock integration and no-till (Guillaume et al., 2022). Singh et al. (2018) summarize a range of studies that found positive effects on SOC storage and soil quality under no-till, addition of organic amendments, higher crop diversity, and light to moderate grazing in crop-livestock farming. Increased SOC stocks were also found (Hajduk et al., 2015) when using cover crops in cropping systems or grasslands (Gravuer et al., 2019; Poeplau & Don, 2015).

Giller et al. (2021) highlight the need for a critical scientific evaluation of RA. With RA's increasing popularity, meta-studies and international studies on the outcome and potential of RA emerge (EASAC, 2022; Lundgren et al., 2021), while farm-based studies in Nordic countries are still lacking. The aim of this study was to test whether the beneficial claims of RA hold up and result in increased soil health in the context of Gotland, Sweden. In practice, RA is adopted by combining different management practices in a wide range of contexts (Soto et al., 2021), and it is necessary to take into account their interference and study the possible different outcomes (Newton et al., 2020). We evaluated the overall impact of different combinations of practices including reduced tillage, application of OM, livestock integration, crop diversity, and share of legumes and perennials. The assessed soil health indicators were bulk density (BD), pH, total organic carbon (TOC), active carbon (AC), microbial biomass carbon and TOC ratio (MBC:TOC), infiltration rate, plant available water (PAW), penetration resistance, root abundance, root depth, earthworm number, vegetation density, C:N ratio, and WAS).

This study was designed based on the hypotheses that (1) there is a difference between soil health indicators under different real-life practices, (2) a correlation can be found between specific practices and overall soil health, and (3) soil texture is similar for all management clusters and is correlated with SOC.

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted on 17 farm fields and six gardens on Gotland (see Figure 1), situated in the Baltic Sea at 57.4°N; 18.5°E. The mean annual temperature and precipitation are 7–8°C and 500–650 mm, respectively (SMHI, 2021). Compared to mainland Sweden, there are milder winters and prolonged summers resulting in a longer growing season. However, the effects of droughts and less predictable weather conditions have also been reported for Gotland, especially since an exceptionally dry summer in 2018 (SMHI, 2022). Lithologically, Gotland consists of limestone and shale clay soils with stripes of clay loams and organic soils, whereas postglacial coarse sand and bedrock are represented along the coast (SGU, 2021; see Figure 1).

Included farms represented a wide range of sizes (0.25–800 ha), type of production (commercial, small-scale sales, or own consumption), and management (vegetable gardens or fields, pastures, and cereal or ley production). A variety of RA practices and combinations were implemented in the different fields (see Supplementary Information for specific management information). Some fields had recently changed their management, whereas others had practiced the same management for up to 30 years. Information about farm management was collected through surveys and personal communication. The included farms were chosen to achieve an overall high variation of management combinations in our study. The fields were chosen together with the farmers. The sampling sites within the fields were chosen by visual assessment of each field, avoiding interference from neighboring land use and areas with irregular vegetation density, compaction, or sloping land.

2.2 | Soil sampling

During the fieldwork in April 2021, soil pits of 50×50 cm area were dug within every field plot until parent material or stone content hindered further digging (between 15 and 50 cm depth, see Supplementary Figure 2 for profile depths and horizons). Detailed profile descriptions were conducted on-site, using Guidelines for soil description (FAO, 2006) and *Bodenkundliche Kartieranleitung* (manual for soil mapping; Ad-hoc-AG Boden, 2005). Three to five undisturbed samples were taken approximately in the middle of the horizons with 203.58 cm^3 cylinders. High gravel and stone content hindered the collection of cylinders from the C horizons of Profiles 5, 12, and 21. Disturbed composite samples from all horizons were taken with a spade, as well as samples for microbial analysis, which were sampled directly into a falcon tube. The latter were kept cooled in the field and frozen within 8 h of collection until further analysis.

2.3 | In-situ measurements

The infiltration rate was measured following an adjusted version of the method used by Van Eekeren et al. (2010), by placing three polyvinyl chloride (PVC) rings with a diameter of 18 cm on the soil close to the soil pit, removing vegetation and recording the time needed for 1 L of water to infiltrate an unsaturated soil. Penetration resistance was measured around the soil pit using an electronic penetrometer (Eijkelkamp, 2010) with 1.0 cm^2 cone base area, a 60° apex angle, and a penetration speed of 2 cm s^{-2}. An average value of the penetration measurements was calculated through the depth of the A-horizon. Vegetation density was

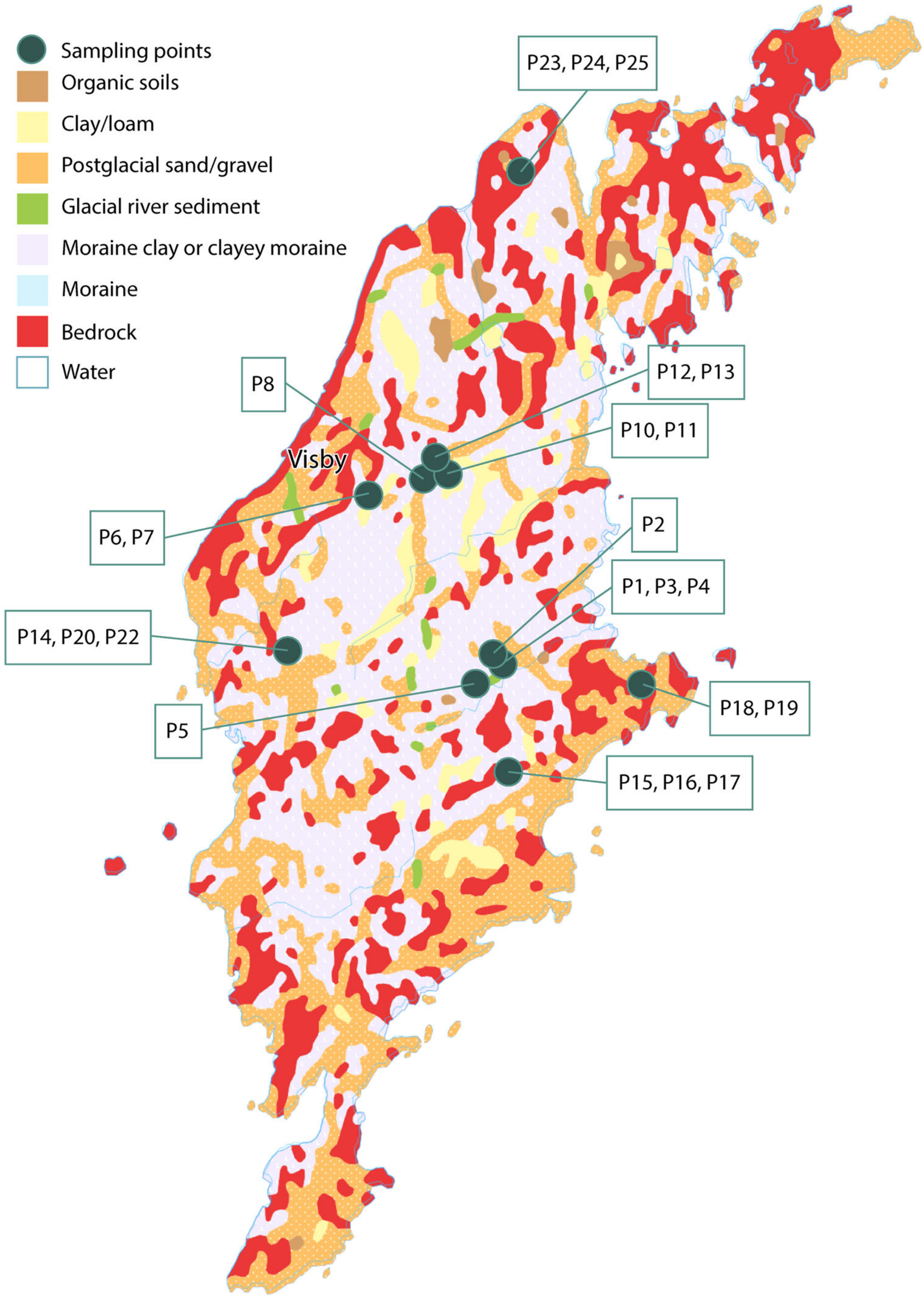


FIGURE 1 Map of Gotland with information on soil types and sampling sites (own illustration after SGU, 2021).

estimated by a visual assessment on the soil surface inside a 50 × 50 cm frame. The lowest reaching roots were measured vertically in each soil profile to determine root depth. The root density was determined by counting the number of roots < 2 mm and > 2 mm on a horizontal 10 × 10 cm area in the A-horizon approximately at 10 cm depth. To estimate root abundance, the amount of medium and coarse roots > 2 mm was multiplied by 10 as recommended in the Guidelines for soil description (FAO, 2006) and added to the amount of very fine and fine roots < 2 mm. Earthworms in the A-horizon were counted after a simplified version of the method by Stroud and Bennet (2018).

2.4 | Ex-situ measurements

For the estimation of BD, the cylinder samples were air-dried until reaching constant weight. Sample preparation for other analyses included air drying, crushing, and sieving of the soil to 2 mm. Soil texture was analyzed according to Van Reeuwijk (2002). Textural classes were determined as < 0.002 mm for clay, 0.002–0.06 mm for silt, and 0.06–2 mm for sand as commonly used in Sweden (Eriksson et al., 2005). pH and electric conductivity (EC) were measured according to ISO 1390:1994 in a ratio of soil:deionized water of 1:5 with a pHenomenal VWR MU 6100 L. PAW was estimated from textural porosity obtained from Saxton and Rawls (2006): 5% for sand, 7% for loamy sand, 1% for sandy loam and sandy clay, and 14% for clay. WAS was determined following the CASH manual (Schindelbeck et al., 2016), using a Cornell Sprinkle Infiltrometer. It was assessed for 0.25–2 mm and > 2 mm aggregates, and a mean value was calculated.

Total carbon and TOC were measured after dry combustion with a vario MAX cube elemental analyzer according to ISO 10694. AC was determined by measuring the $KMnO_4$-oxidizable C fraction with a spectrophotometer following the CASH manual (Schindelbeck et al., 2016). MBC was determined with the chloroform fumigation extraction method, using a protocol by Shi and Spångberg (2019) after Brookes et al. (1985) and Vance et al. (1987). The TOC analysis for the determination of MBC was done in a multi N/C 2100 S direct injection TOC analyzer by catalytic high-temperature combustion up to 950°C using Focus Radiation Non-dispersive infrared spectroscopy (NDIR).

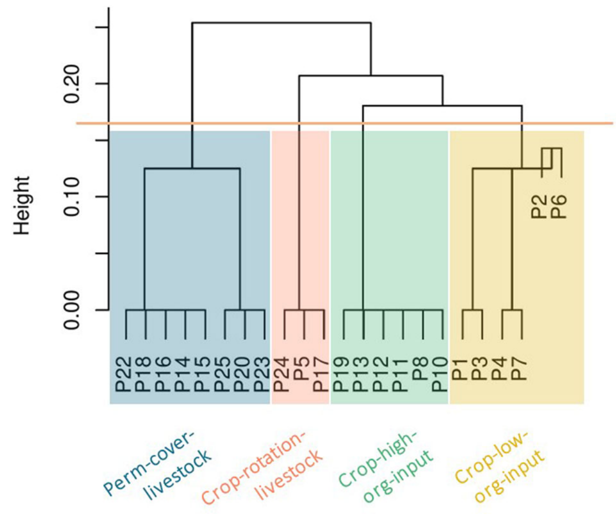


FIGURE 2 Groups of field plots classified through hierarchical partitioning clustering.

2.5 | Data and statistical analysis

2.5.1 | Field management

Data analysis was performed using R Statistical Software, version 4.0.4 (R Core Team, 2021). Unless specified, functions were included in the *base* packages (R Core Team, 2021). Only A-horizons were considered in statistics.

The 23 field plots were classified according to the scaled management parameters from the last 6 years (beginning of 2015 to spring 2021): years without tillage, amount of C added through organic amendments, crop diversity index (CDI) after Tiemann et al. (2015), permanent coverage of the field (yes/no), use of cover crops (yes/no), percentage of legumes, perennials (without trees), and trees, integration of livestock (yes/no) and use of synthetic inputs (yes/no), including mineral fertilizers, pesticides, herbicides, and fungicides. Hierarchical partitioning clustering with the default algorithm of Hartigan and Wong (1979) of the *k-means* function from the *stats* package (R Core Team, 2021) was performed to group the fields based on management indicators. The resulting number of four clusters was determined after assessing results with different amounts of clusters and how they related to the input values.

2.5.2 | Soil health indicators

All soil data were saved in tidy data format via the *tidyverse* package (Wickham et al., 2019) and were centered to their respective means and scaled for a principal component analysis (PCA). Score, loading, and biplots and a loading and score matrix were created for principal component 1 (PC1) and principal component 2 (PC2). The *compositions* (Boogaart et al., 2021) and *ggbiplot* (Vu, 2011) packages were used for the biplot. PC1 and PC2 were extracted to be used for further analysis. Corresponding plots were made using the *ggplot2* package (Wickham, 2016).

Type II-Analyses of Variance (ANOVAs) for the multiple linear regression (MLR) models and management clusters were calculated with the *stats* package (R Core Team, 2021). Tukey's post-hoc test was performed for pairwise comparisons of practices, soil health indicators and soil texture between management clusters Shapiro–Wilk tests were applied to check the null hypothesis of a normal distribution of the ANOVA residuals, as well as normal Q–Q plots to visually check for normality of residuals, residuals versus fitted plots to check for homoscedasticity (or constant variance) and predicted versus actual value plots. Boxplots showing medians, min, and max values among the clusters were made (see Supplementary Information) using the *ggpubr* package (Kassambara, 2020). The *soiltexture* package was used for visualization of particle size distributions (Moeys, 2018).

3 | RESULTS

3.1 | Field management

Comparing practices among the four management clusters through ANOVAs resulted in a sum of squares between clusters/total sum of squares of 71.4%. Figure 2 shows the division of field plots into clusters. Across the four management clusters, fields were characterized in the following way (see also Supplementary Table 1):

(1) *crop-high-org-input*: This group included six vegetable fields with no synthetic inputs, high amount of added C through OM permanent cover or cover crops, reduced or no tillage (5–6 years), low inclusion of legumes and perennials (< 20%), and no livestock. This management cluster had a significantly higher value of years without tillage, compared to *crop-low-org-input* (°), and a significantly higher amount of C added through OM, compared to *crop-low-org-input* (***), *perm-cover-livestock* (***), and *crop-rotation-livestock* (**).

(2) *crop-low-org-input*: This group included six crop fields with synthetic amendments, including mineral fertilizer, and pesticides, low amount of C added through OM (0–16.2 t C), no livestock, low CDI (1.0–7.5), no permanent cover, low inclusion of legumes (<20%) and varied tillage intensity (0–6 years). This management cluster had a significantly higher share of legumes than *crop-high-org-input* (°) and significantly lower than *crop-rotation-livestock* (***).

(3) *perm-cover-livestock*: This group included eight grazing fields with permanent cover, medium CDI (16–36), high inclusion of perennials (> 70%), low inclusion of legumes (<30%), low amount of C added (< 2.3 ton C ha^{-1}), no synthetic input, inclusion of livestock, and no tillage. This management cluster had a significantly higher crop diversity than *crop-high-org-input* (*) and *crop-low-org-input* (*), a significantly higher share of perennials than *crop-high-org-input* (***) and *crop-low-org-input* (***), a significantly higher value of years without tillage, compared to *crop-low-org-input* (*).

(4) *crop-rotation-livestock*: This group included three crop rotation fields with no added synthetic amendment, inclusion of cover crops, no permanent cover, inclusion of legumes (50%–70%) and perennials excl. trees (60%–80%), periodical grazing of livestock, and reduced tillage (3–5 years). This management cluster had significantly higher crop diversity than *crop-high-org-input*(*) and *crop-low-org-input*(***), a significantly higher share of perennials than crop-high-org-input (***) and *crop-low-org-input* (**), a significantly higher share of legumes than the other three clusters (***).

3.2 | Soil texture and PAW

The texture in our samples ranged from clayey loam to sandy clayey loam, sandy loam, loamy sand, and sand. Figure 3 shows the particle size distribution of the field plots in the texture triangle. Percentages of sand (*) and silt (*) content were significantly different between the clusters *perm-cover-livestock* and *crop-low-org-input*. Fields of *perm-cover-livestock* had up to >90% sand, while fields of *crop-low-org-input* generally had a lower sand content with <70% sand. Fields of *crop-high-org-input* and *crop-rotation-livestock* were well-distributed between the mentioned texture classes. No significant correlation was found between clay or sand content and the amount of soil organic C in the dataset. The texture-based PAW was on average lower for *perm-cover-livestock* with a median of 7% than for the three clusters with higher clay content, all with a median of 10% (see Table 1), but no significant differences were found for PAW between the clusters.

3.3 | Soil health related to management clusters

Comparing the soil health indicators between the four management clusters through ANOVAs, we found a significant difference in the soil health indicators infiltration rate (**), root abundance (**), earthworms (*), vegetation density (***), TOC (*), and C:N (*). No significant difference was found for pH, AC, TOC, WAS, penetration resistance, and root depth. Table 1 shows median, minimum, and maximum values for soil health indicators between the management clusters.

Crop-high-org-input, with the highest input of organic amendments with a median of 63.3 ton C ha^{-1} (see Supplementary Table 1), had the highest TOC and C:N levels of 54 g C kg^{-1} soil and 112, respectively. The other three clusters with organic amendments added in the range of 0.6–7.6 ton C ha^{-1} had a similarly low level of TOC and C:N, with a median range of 20–24 g C kg^{-1} soil and 8.7–9.4, respectively (see Table 1). A significant difference was found for TOC between *crop-high-org-input* and *crop-low-org-input* (°) and *perm-cover-livestock* (*) and for C:N ratio between *crop-high-org-input* and *crop-low-org-input (*)*. A significant difference was detected for earthworms between *crop-high-org-input* and *crop-low-org-input* (*) and *perm-cover*-livestock (*) and for infiltration rate between *crop-high-org-input* and *crop-low-org-input* (°), *perm-cover-livestock* (**), and *crop-rotation-livestock* (*). C*rop-high-org-input* had the highest median values for earthworm abundance and infiltration rate of 17.5 individuals per 50 × 50 cm soil pit and 172 mm h^{-1}, respectively, while the other three clusters had similarly lower medians of less than six individuals per 50 x 50 cm soil pit and <70 mm h^{-1}; see Table 1. However, *crop-rotation-livestock* had the highest maximum earthworm value of 26 individuals per 50 × 50 cm soil pit (Table 1). A significant difference was detected for root abundance between *perm-cover*-livestock and *crop-high-org-input* (**) and *crop-low-org-input* (**). A significant difference was detected for vegetation density between *perm-cover-livestock* and *crop-high-org-input* (***) and *crop-low-org-input* (***) and between *crop-rotation-livestock* and *crop-high-org-input* (***) and *crop-low-org-input* (*). The group of *perm-cover-livestock* had the highest median values for root abundance and vegetation density, 85% and 100%, respectively, followed by *crop-rotation-livestock* with 60% and 80% (see Table 1). The median of root abundance was 30 roots and 32.5 roots for *crop-high-org-input* and *crop-low-org-input*, respectively. Vegetation density median values were 40% for *crop-low-org-input*, and 1% (Table 1) for *crop-high-org-input*, both with one higher outlier (see supplementary Figure 1).

3.4 | Combined soil health indicators related to management practices

Figure 4 shows the PCA biplot with related loadings for PC1 and PC2. PC1 and PC2 are characterized by two groups of variables. PC1 was mainly described by BD and MBC:TOC with a negative impact and AC, TOC, C:N ratio, WAS, and infiltration rate with a positive impact, hereinafter referred to as *C-related parameters*. This is confirmed by a strong relationship between the amount of C added and PC1 in a MLR (***) (see Figure 5) and a significant difference in scores on PC1 for *crop-high-org-input*, compared to *crop-low-org-input* (*), *perm-cover-livestock* (**), and *crop-rotation-livestock* (*).

PC2 was positively influenced by pH, earthworm number, and PAW and negatively by vegetation density, root abundance, and depth as a dense cluster as well as sand and WAS (Figure 4), hereinafter referred to as *structural parameters*, excluding sand. The best performing MLR with PC2 included significant relationships with years without tillage

TABLE 1 Soil health indicator summary between management clusters.

Indicator		Crop-high-org-input	Crop-low-org-input	Perm-cover-livestock	Crop-rotation-livestock
BD (g cm^{-3})	Min	0.58	1.21	1.14	1.32
	Median	1.16	1.44	1.44	1.33
	Max	1.62	1.63	1.57	1.38
EC (μS cm^{-1})	Min	142.1	92.6	52.9	144.2
	Median	357.0	185.3	175.3	179.3
	Max	745.0	274.0	284.0	229.0
TOC (g C kg^{-1} soil)	Min	17.4	11.1	10.8	19.5
	Median	53.8	21.4	20.4	24.1
	Max	93.2	37.2	40.9	28.5
AC (g C kg^{-1} soil)	Min	2.14	2.25	1.91	2.40
	Median	2.75	2.52	2.38	2.51
	Max	2.93	2.68	2.88	2.52
C:N (–)	Min	8.28	6.95	8.06	8.88
	Median	11.17	8.72	9.38	9.19
	Max	12.54	10.34	10.76	10.04
MBC:TOC (–)	Min	0.73	1.34	0.65	1.69
	Median	1.19	1.54	2.63	1.72
	Max	2.60	2.93	3.96	3.20
WAS (%)	Min	53.6	56.6	66.8	61.4
	Median	80.4	69.9	82.2	73.4
	Max	98.8	87.7	90.8	78.0
Earthworm numbers (–)	Min	0	1	1	4
	Median	17.5	3	3.5	6
	Max	20	10	8	26
Vegetation density (%)	Min	0	0	90	75
	Median	1	40	100	80
	Max	30	100	100	100
Root abundance (–)	Min	10	15	40	50
	Median	30	32.5	85	60
	Max	60	50	130	70
Root depth (cm)	Min	15	32	25	40
	Median	31	36	41	48
	Max	50	40	55	50
Infiltration rate (mm hour^{-1})	Min	103	16	8	29
	Median	172	63	56	70
	Max	253	206	171	82
Penetration resistance (MPa)	Min	1.04	1.03	1.29	1.51
	Median	1.92	1.92	1.61	1.57
	Max	2.57	3.37	2.38	1.69
PAW (% volume)	Min	7	7	5	7
	Median	10	10	7	10
	Max	10	14	10	10

Abbreviations: BD, bulk density; EC, electric conductivity; TOC, total organic carbon; AC, active carbon; C:N, organic carbon to total nitrogen ratio; MBC:TOC, microbial biomass carbon to TOC ratio; WAS, wet aggregate stability; PAW, plant-available water.

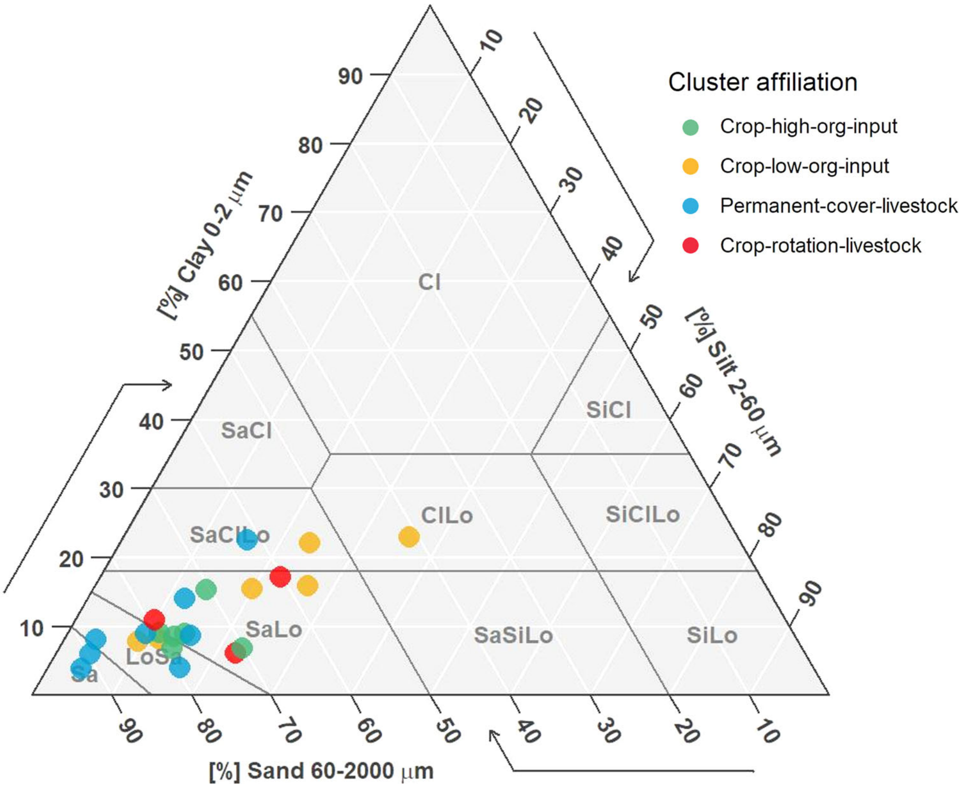


FIGURE 3 Soil texture of field plots displayed in texture triangle.

TABLE 2 ANOVAs of multiple linear regressions with (1) PC1 and amount of C added and (2) PC2 and years without tillage + share of perennials.

	ANOVA				
	c_add	till	per	adjusted R^2	Shapiro–Wilk (residuals)
PC1	***	–	–	0.54	$p = 0.65$
PC2	–	°	*	0.30	$p = 0.34$

Abbreviations: c_add, carbon added (t ha^{-1}), average over the period 2015–220 after Tiemann et al. (2015); till, years without tillage, cumulative value over the period 2015–2020; per, share of perennials (%), PC1, principal component 1; PC2, princpal component 2.
*** $p < 0.001$, * $p < 0.05$, ° $p < 0.1$.

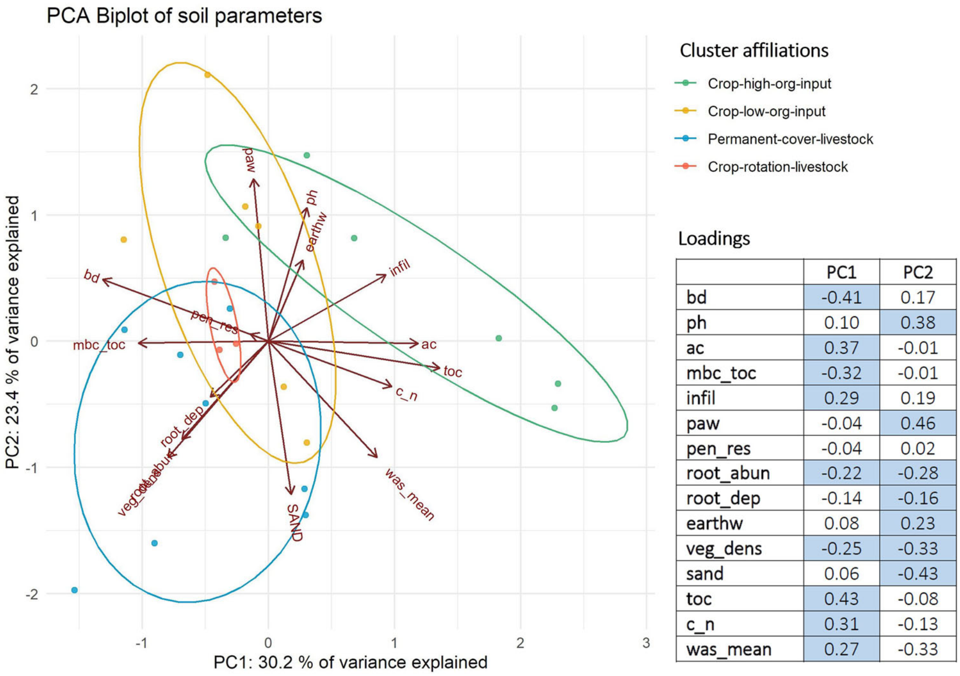
(°) and share of perennials (*) (see Table 2). Comparing the management clusters, we found a significant difference in scores on PC2 for *perm-cover-livestock*, compared to *crop-low-org-input* (*). Penetration resistance had a low score on both PC1 and PC2 and is thus represented by neither of the two PCs.

4 | DISCUSSIONS

The focus of this study was to explore correlations between combined and single regenerative practices and soil health on Gotland, Sweden, as well as to examine if textural differences interfered with the outcomes, based on measurements on 23 fields. Fields were classified into four management groups based on hierarchical partitioning clustering, and we found a significant difference in particle size distribution between *perm-cover-livestock* and *crop-low-org-input*. A strong significant relationship was found between amounts of organic amendments and BD, MBC:TOC, AC, TOC, C:N ratio, WAS and infiltration rate, and a significant relationship between reduced tillage combined with an increasing share of perennials and pH, earthworm number, PAW, vegetation density, root abundance and depth, sand, and WAS. We found significant differences in soil health indicators between the four clusters of management practices. Henceforth, we will discuss how the results of this study relate to existing literature, the impact of texture on our results, the relationship between organic amendments and C-related parameters, and the impact of reduced tillage, and the integration of perennials on structural indicators. We will also discuss the suitability of *crop-low-org-input* as a control cluster. Finally, we will reflect on how the results of this study can help expand the scientific discussion behind political and regulatory frameworks in relation to RA.

4.1 | The influence of texture on soil health indicators

Texture is an inherent soil property and generally cannot be influenced by management. The particle size distribution of a soil is however highly relevant for farm operations, management decisions, and influences how a soil reacts to changes in management. In this study, a significant difference in particle size distribution was found between



	PC1	PC2
bd	-0.41	0.17
ph	0.10	0.38
ac	0.37	-0.01
mbc_toc	-0.32	-0.01
infil	0.29	0.19
paw	-0.04	0.46
pen_res	-0.04	0.02
root_abun	-0.22	-0.28
root_dep	-0.14	-0.16
earthw	0.08	0.23
veg_dens	-0.25	-0.33
sand	0.06	-0.43
toc	0.43	-0.08
c_n	0.31	-0.13
was_mean	0.27	-0.33

FIGURE 4 Biplot of principal component analysis with PC1 and PC2, showing loadings and scores, grouped in management clusters

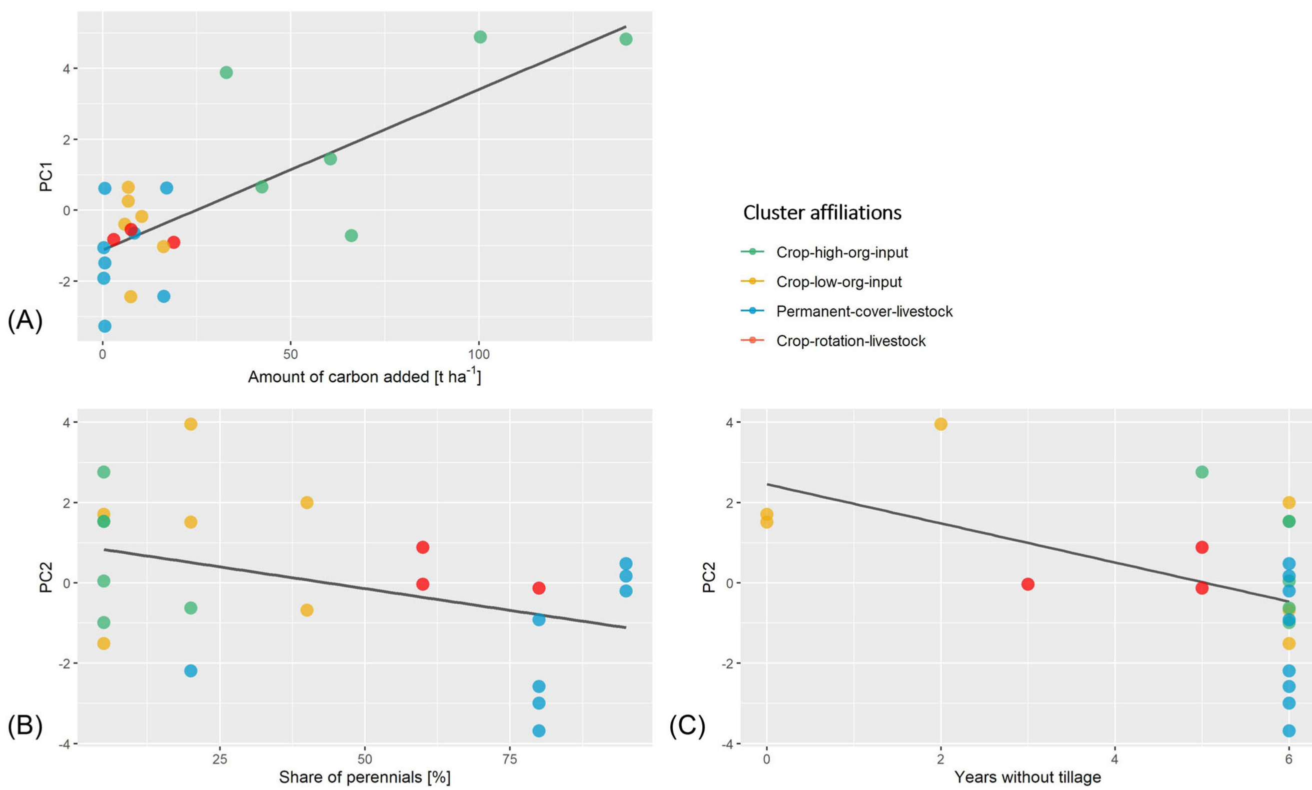


FIGURE 5 Separate visualization of the linear regression model with (A) PC1 and amount of carbon added, (B) PC2 and share of perennials, and (C) PC2 and years without tillage.

the two clusters *crop-low-org-input* with a higher percentage of sand and *perm-cover-livestock* with a higher percentage of clay represented. Generally, the amount of stored SOC is a function of added OM and soil texture, and SOM is less protected in coarse-textured soils than in finer-textured soils (Giller et al. 2009). This may explain why we see lower results for C-related parameters for *perm-cover-livestock*, even though fields with intermediate grazing have some of the highest potential for storing C (Ward et al., 2016). Rotational grazing is considered a best practice in RA, as it uses few external inputs, promotes biodiversity, animal welfare, and results in high-quality products (EASAC 2022).

When further looking at the relationship between TOC to texture, we found no correlation with sand or clay content, as the investigated soils were predominantly sandy. Other studies on soil health comparing soils across a broader variety of soil textural classes (e.g., Liptzin et al., 2022) reported a relation between sand or clay content and SOC. Clayey soils generally have a greater OM content than silty or sandy soils with similar C influx and climatic conditions (Blume et al., 2018). Singh et al. (2018) even suggest the addition of clay to sandy soils as a management practice to increase SOC, and Liptzin et al. (2022) found a higher clay content related to higher values for soil health.

4.2 | The influence of management on soil health indicators

Several studies suggest improved effects by combining regenerative practices: Soto et al. (2021) report overall better soil quality restoration with combined treatments of reduced tillage with green manure and organic amendments than individual practices. Xu et al. (2019) found that cover cropping combined with organic amendment addition reduced BD and increased OM content and water holding capacity significantly within 1.5 years in comparison to cover cropping alone. Blanco-Canqui and Ruis (2018) describe the additive positive effect on soil physical properties of so-called “companion practices” like crop-livestock integration, cover crops, rotations with perennials, the addition of animal manure, and diversified cropping systems in no-till systems. Nunes et al. (2018) show positive long-term effects of no-till on soil health and crop yields that are enhanced in combination with crop rotations and cover crops. Liu et al. (2022) find increased aggregate stability and SOC with no-till and significant positive effects from legumes under no-till, and Junge et al. (2020) reported improved soil structure with a combination of no-till and mulching/ cover crops. A report by EASAC (2022) summarizes the effects of different practices on C storage and biodiversity for European agriculture: potentially highest positive impacts lie in crop diversification, the integration of trees in arable land and all-year soil cover.

In this study, a positive impact of OM additions on the agglomerated parameters TOC, AC, BD, C:N ratio, WAS, and infiltration rate was detected. A negative relation was found between increased organic amendments and MBC:TOC, which may be explained by a relatively higher increase in TOC. The management cluster *crop-high-org-input* represented a combination of the regenerative practices no-till and high organic inputs and showed significantly higher values for TOC, C:N ratio, infiltration rates, and earthworms than other clusters. Similar correlations have been reported by Liptzin et al. (2022), who found that C-related indicators correlated with each other and responded positively to the amount of OM addition. OM addition is a regenerative practice suggested for carbon capture and storage, with additional benefits of soil and biodiversity restoration (EASAC, 2022). Bhogal et al. (2018) support that there are soil quality benefits of the addition of OM, but both the quantity in terms of C content and the quality in terms of decomposability play an important role. Especially the amount of biologically available C sources is essential for biological and physical soil functions. This brings up a contradiction between two major soil health goals, (1) C storage and (2) increased microbial activity, causing C mineralization (e.g., Kandeler et al., 2005). Waring et al. (2020) underline that all living organisms depend on C and nutrient cycling through the terrestrial food web and not on C storage. C inputs and SOC stocks have a non-linear relationship, influenced by factors that cannot be detected at the scale of our study. Such include microbial accessibility to C, decomposition rates influenced by the heterogeneity of soil, the priming effect of fresh C inputs that can increase SOC losses, or the release of mineral-protected C through destabilization effects of root exudates. Leifeld and Keel (2022) conclude that both permanent and reversible SOC sinks have a positive climate effect, even if the impact of the latter is substantially smaller.

In the MLR, we found that a combination of reduced tillage and share of perennials had a positive impact on vegetation density, root abundance, and depth. *Perm-cover-livestock*, the cluster with 100% share of perennials, and no tillage showed significantly higher values of root abundance and vegetation density. Vegetation density, root abundance, and depth are influenced by land use and soil type. Naturally, reduced or no tillage occurred on fields that were dominated by perennial plants and livestock integration, which in turn score higher on vegetation and root growth due to the absence of disturbance for the growth. *Crop-high-org-input* fields had a high amount of annual vegetable crops with no cover crops integrated, causing low values of crop diversity and associated vegetation density and root abundance due to more frequent disturbance through harvest and other operations. *Crop-rotation-livestock* had high values on vegetation density and root abundance and the highest median on root depth. The inclusion of grazing animals within the crop rotation resulted in a longer time without tillage or harvest creating time for perennials to establish. We took the samples in the spring, after a year with animal grazing in the previous autumn at two out of three fields in the cluster. Thus, sampling was conducted in a year with optimal conditions for vegetation growth within the rotation. EASAC (2022) highlights all-year soil cover and crop diversification as some of the regenerative practices with the potentially highest positive impact on C storage and aboveground biodiversity.

We did not measure any increase in SOC in the topsoil with reduced or no tillage, in contrast to, e.g., Al-Kaisi and Kwaw-Mensah (2020) and Gadermaier et al. (2011). Haddaway et al. (2017), updated by Meurer et al. (2018), conducted a systematic review on 351 studies and found that no-till and conservation tillage had a potential of increasing SOC in the topsoil (0–30 cm) but not in greater depths, in contrast to high and intermediate tillage intensity. Our results of increased vegetation density, root growth and root depth, and WAS with reduced tillage and increased share of perennials correspond with the observed positive correlations between structural parameters and reduced tillage found by Abdollahi et al. (2017).

From the MLR, we found an increase in WAS with the combined practices of reduced tillage and increased share of perennials. Similarly, WAS was higher, though not significantly, for the two clusters representing fields with no tillage, *crop-high-org-input* and *perm-cover-livestock*. Recent additions of OM to soil are primarily found in macroaggregates, which are also more susceptible to destruction by tillage than smaller aggregates. The subsequent decomposition and C loss is thus especially high in the larger aggregate fraction (Blume et al., 2018) and a combination of reduced tillage and organic amendments can be beneficial for improved SOC storage (Soto et al., 2021).

Crop-low-org-input, the cluster management with the fewest regenerative management practices represented, did not score highest on any soil health indicator. In soil health studies, a baseline or control group should be included to enable the identification of management effects (Bünemann et al., 2018). *Crop-low-org-input* could possibly act as a control cluster, scoring lowest on most management indicators. However, this cluster had a varied range of years without tillage, which represents one of the main management practices that were evaluated. The function of *crop-low-org-input cluster* as a control group is thus limited. Synthetic amendments were only represented in the group of *crop-low-org-input* and could create a bias in our dataset.

4.3 | RA in the political environment

Many practices mentioned in the context of RA are found in a wide range of farming systems (Bossio et al., 2020; Project Drawdown, 2020; Toensmeier, 2016) and have existed for centuries within Indigenous agriculture (Heim, 2018). While they are now reframed as regenerative, they are generally considered *good agricultural practices* (Giller et al., 2015), and the importance lies not in their label but in their capacity to relieve pressures on agricultural land. Newton et al. (2020) identify three main issues with RA being a largely undefined term: First, verifying claims about the impact of RA can be challenging for scientists without clear terminology. Second, labeling and marketing can be misleading for consumers. Third, policies, laws, and (public) incentives to support RA are difficult to argue for without a widely accepted perception of the concept and clear guidelines. This stresses the importance of a commonly accepted, yet context-specific definition of RA, on which incentive and marketing schemes can be based.

In the New Common Agricultural Policy of the EU at least 25% of direct payments must be paid for so-called “eco schemes,” under which carbon farming is mentioned (European Commisssion, 2021b, 2021c, 2021d). The New Soil Strategy (European Commisssion, 2021a, 2021b, 2021c, 2021d) underlines the economic and social risks of soil degradation and states that the cost of not transitioning to sustainable and potentially regenerative practices outweighs the cost of implementation by a factor of six in Europe. Many of the objectives in the New Soil Strategy can be related to claimed outcomes of RA practices, for example, to achieve a net GHG removal of 310 million tonnes CO_2 equivalents per year by 2030, to achieve land-based climate neutrality by 2035, or to reach no net land take by 2050. A goal of the strategy is to develop indicators for soil health and their ranges on an EU level, to be specified in the Soil Health Law by 2023 and achieved by 2050 (European Commisssion, 2021a). Examples of EU co-funded agriculture projects on Gotland are “Sustainable Speis” (Tillväxt Gotland, 2022) with its aim to promote the island as a sustainable food destination and a series of seminars on RA from March to June 2022, organized by the island’s county board (Länsstyrelsen Gotland, 2022). This study is the first to find evidence that adapting regenerative practices on Gotland soil can improve soil health and thus CC resilience. However, no panacea for C sequestration or soil health exists. The storage capacity of SOC highly depends on climate, soil, and landscape characteristics as well as historic C losses from the soil. Activities that build organic C in one soil might be ineffective in another soil (Bossio et al., 2020; Lal et al., 2018). Further, other biophysical, social, economic, and cultural considerations must be made to tackle context-specific challenges. This includes a wide variety of starting points, agroecosystems, scales of operation, policies, food systems, and so forth (Giller et al., 2021; Lal et al., 2018). Hence, no one specific set of practices or meaningful definition can be made to address all challenges alike and the option for contextualization and local adaptation in new policies is imperative. Innovative forms of evaluating and monitoring progress will have to be created, to assess changes in SOC, soil health, and possible co-benefits or trade-offs within RA alike.

5 | CONCLUSION

Assessing regenerative management practices, our results demonstrate a general positive impact on soil health on our fields on Gotland. By comparing four management clusters, we found significant differences in soil health results for the cluster *crop-high-org-input*, which was characterized by a high amount of C added through organic amendment and no tillage, on the soil health indicators: TOC, C:N, earthworm abundance, and infiltration rate. The median value for *crop-high-org-input* on TOC was 33 g C kg^{-1} soil higher than *perm-cover-livestock*, 32 g C kg^{-1} soil higher than *crop-low-org-input*, 30 g C kg^{-1} soil higher than *crop-rotation-livestock*. The median value for *crop-high-org-input* on C:N was 2.5 higher than *crop-low-org-input*, 1.98 higher than *crop-rotation-livestock*, and 1.79 higher than *perm-cover-livestock*. The median value for *crop-high-org-input* on earthworm numbers was 14.5 individuals per 50 × 50 cm higher than *crop-low-org-input*, 14 individuals per 50 × 50 cm higher than *perm-cover-livestock*, and 11.5 individuals per 50 × 50 cm higher than *crop-rotation-livestock*. The median value for *crop-high-org-input* on infiltration rates was 116 mm h^{-1} higher than *perm-cover-livestock*, 109 mm h^{-1} higher for *crop-low-org-input*, and 102 mm h^{-1} for *crop-rotation-livestock*.

We found that vegetation density and root abundance were higher for the livestock fields *perm-cover*-livestock and *crop-rotation-livestock*, which included a higher share of perennials combined with reduced or no tillage. The median value for *perm-cover-livestock* on vegetation density was 20% higher than *crop-rotation livestock*, 60% higher than *crop-low-org-input*, and 99% higher than *crop-high-org-input*. The median value for *perm-cover-livestock* on the root abundance index was 25 higher than *crop-rotation-livestock*, 53 higher than *crop-low-org-input*, and 55 higher than *crop-high-org-input*. By assessing MLRs between different combinations of practices, we observed a positive impact from C added through organic amendments on the indicators BD, AC, TOC, C:N ratio, WAS and infiltration rate and a positive impact from reduced tillage combined with an increasing share of perennials on the indicators vegetation density, root abundance and depth, and WAS.

A large potential is held in RA to be a framework for agricultural development toward improved soil health and CC mitigation and adaptation. While many alternative agricultural approaches with sustainable aspects exist today, and many of the promoted practices in RA have been deployed before, we see an increasing use and enthusiasm. Promoted practices in RA can have a positive effect if they are appropriate for the ecological, climatic, economic, and social context. We advocate for a context-dependent, dynamic, and ever-evolving definition of the concept. Clarifying the meaning, principles, and anticipated outcomes of RA for specific contexts is important for policy decisions and to avoid co-option and greenwashing.

In this study, we could show regenerative farming on Gotland positively impacts soil health, with combinations of multiple practices like the addition of OM, reduced tillage, and increased share of perennials yielding the best results in soil health. Through improved soil health, regenerative practices have the potential to help increase resilience against CC disturbances, thus achieving higher food security. Further research is needed to study the combined effect of a variety of regenerative management practices in different agricultural contexts.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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