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ORIGINAL PAPER

Context Matters: Soil Ecosystem Status Varies across Diverse Conservation Agriculture Systems

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Abstract
Conservation agriculture promotes soil health across different management and environmental contexts. While soil ecosystem status (health and functioning) serves as a key indicator of soil health, it remains understudied, with most evidence coming from long-term trials that may not reflect on-farm conditions. Therefore, this study evaluated and compared the long-term soil ecosystem status (health and functioning) of farmer croplands practicing conservation agriculture under two distinct management and environmental contexts. Two sites near Vrede and Reitz (South Africa) were investigated, focusing on conservation agriculture systems, with conventional agriculture and grazed grassland as references systems. Selected ecological indicators (nematode-based indices, organic matter, permanganate-oxidizable carbon, and soil respiration) and physico-chemical properties (particle size distribution, pH, electrical conductivity, and macro- and micronutrients) were assessed to measure soil ecosystem status and the environmental context. At Vrede, pasture and conservation agriculture systems presented elevated organic matter content and microbial activity due to continuous organic cover and minimal physical disturbance. Furthermore, the nematode Maturity Index in these systems was higher, indicating more balanced and healthier soil ecosystems. In contrast, at Reitz, differences between conservation agriculture systems were strongly associated with soil texture differences, influencing organic matter and respiration rates. Additionally, fine-textured soils consistently exhibited greater permanganate-oxidizable carbon values, reflecting the role of soil texture in carbon retention and ecosystem functioning. This study underscores the relevance of both agricultural management and environmental contexts, particularly soil texture, when implementing conservation agriculture systems. It highlights the need for tailored agricultural systems to complement on-farm options and local conditions.

Keywords Agricultural systems · Ecological indicators · Environmental conditions · Soil health · Sustainable agriculture

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1 Introduction

Soil health is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (NRCS 2024) and is widely accepted as a key concept in promoting environmental health and food security (Bagnall et al. 2021; Bünemann et al. 2018). As a result, the design and implementation of agricultural systems aimed at restoring and maintaining healthy soils have increased in recent years (Khangura et al. 2023; Montgomery and Biklé 2021; Wezel et al. 2020). Conservation agriculture, sometimes referred to as regenerative agriculture, is one such system and is characterised by three main principles, namely (1) minimal or no soil disturbance, (2) permanent organic soil cover, and (3) crop diversification through crop rotation or integration of cover crops (Brown

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et al. 2018; Hobbs et al. 2008; Thierfelder and Mhlanga 2022). According to Kassam et al. (2022) global annual increases in the adoption of conservation agriculture is typically greater than 10 M ha. Driving this interest from farmers is the reported benefits of conservation agriculture, including increased carbon sequestration (Kiran Kumara et al. 2020) and water use efficiency (Jat et al. 2020), as well as increased yields and profits especially under limited rainfall conditions (Thierfelder and Mhlanga 2022). Conservation agriculture has also been linked to increased ecosystem multifunctionality, including biodiversity preservation, soil and water quality, and climate mitigation (Wittwer et al. 2021). However, changes in soil health status and the manifested benefits or pitfalls must be monitored to inform farmers and land managers of the restoration rate and whether intervention is required (Muñoz-Rojas 2018).

Generally, soil health assessment and monitoring frameworks make use of selected physical, chemical, and biological indicators integrated to calculate a soil health score (Cherubin et al. 2016; Moebius-Clune et al. 2016a, b). However, in practice, soil health studies frequently lack an ecological perspective, meaning they do not properly focus on the biological component of soil health (Sprunger and Martin 2023). Biological measurements would often be limited to microbial biomass and soil respiration (Bünemann et al. 2018). But given the central role that soil biology plays, several authors have emphasised the need to focus on soil ecosystem status. Information on soil ecosystem status can be generated by studying nematode communities (Du Preez et al. 2022). Nematodes occupy an important position in the soil food web where they interact closely with other organisms across trophic levels (Creamer et al. 2022; Li et al. 2024; Neher 2001). They regulate microbial populations, assist in nutrient cycling, and contribute to the activation of plant defensive mechanisms and the introduction of antagonistic bacteria of plant pathogens (Li et al. 2024; Topalović and Geisen 2023). Finally, nematodes are very responsive to changes in the soil environment including food availability and chemical or physical disturbances (Bongers and Ferris 1999; Carneiro et al. 2019; Du Preez et al. 2018; Sánchez-Moreno et al. 2018), making them indicators of soil ecosystem health and functioning over temporal and spatial scales (Ney et al. 2019).

However, a limited focus on ecosystem status as part of soil health assessments is not the only challenge in generating a sound scientific understanding of the benefits and pitfalls of conservation agriculture. Much of the science related to conservation agriculture has been performed in managed long-term research trials, such as the Langgewens Research Trial (South Africa) (Labuschagne et al. 2020; Mulimbi et al. 2023) and the W. K. Kellogg Biological Station Long-term Ecological Research experiment (USA) (Martin and Sprunger 2022; Sprunger et al. 2020). These trials are key to studying plant-soil interactions and ecological responses over multiple years, especially considering that soil ecosystem recovery takes time (Du Preez et al. 2024). Yet, in practice, conservation agriculture is implemented under a multitude of management and environmental contexts with varying success rates (Smith et al. 2022; Thapa et al. 2023).

Agricultural practices like composting, integration of livestock, judicious use of fertilizers, and agroforestry are often implemented in addition to the main principles of conservation agriculture (FAO 2013; Lal 2020; Thierfelder et al. 2018). Farmers' risk tolerance and limited capital also affect their adoption of these practices, as does the local environmental context. For instance, a study by Du Preez et al. (2024) in South Africa noted that while conservation agriculture improves soil health, local sandy conditions restrict carbon storage, which in turn affects ecological processes. In addition to soil characteristics, climatic factors also play an important role in determining the carbon storage potential of soils. In semi-arid dryland conditions, limited rainfall restricts crop growth, which reduces the carbon inputs available for sequestration (Halvorson et al. 2002). With fewer carbon inputs, the soils' capacity to accumulate organic carbon is inherently constrained. Moreover, prolonged periods of high temperatures, coupled with low soil moisture, further restrict microbial activity that is key for the breakdown and stabilisation of organic matter (Morell et al. 2011). A review on conservation agriculture in arid and semi-arid conditions revealed large ranges (28–66%) in soil organic carbon sequestration (Page et al. 2020). Ultimately, we need to understand that substantial variability is associated with conservation agriculture and most importantly, that it is not a 'one-size-fits-all' approach (Lal 2020). Furthermore, there is a need for on-farm research, which usually involves farmer-led research trials often supported by a scientific team (Jackson-Smith and Veisi 2023). This approach offers a unique opportunity to evaluate the efficacy and performance of conservation agriculture under the different management and environmental contexts that farmers operate within (Snapp et al. 2019; Strauss et al. 2021).

Given the integral role of soil ecosystems in determining the success of conservation agriculture and the potential for varied responses due to different management and environmental contexts, this study aimed to evaluate and compare the long-term soil ecosystem status of farmer croplands practicing conservation agriculture under two distinct management and environmental contexts. Therefore, the first objective was to investigate the effect of conservation agriculture under two distinct management contexts on selected ecological indicators of soil ecosystem health and functioning. Secondly, we evaluated the ecological responses of soil under conservation agriculture to the environmental context, as reflected by selected soil physical and chemical properties. Finally, this study sought to explore the practical implications for farmers and inform the implementation of conservation agriculture.

We hypothesise that conservation agriculture systems promote soil ecosystem health and functioning, but its effectiveness is influenced by management practices and environmental conditions, with ecological responses linked to variations in soil physical and chemical properties.

2 Materials and Methods

2.1 Study Sites

The study was undertaken in the Free State Province, a semi-arid region within a summer rainfall area of South Africa (Hensley et al. 2006). Two farms represented the study sites and were located near the town of Vrede and Reitz, respectively. These farming sites are approximately 90 km apart and situated at elevations of 1600 m (Vrede) and 1700 m (Reitz) above sea level. Both sites are in the Highveld Grassland climatic region, characterised by warm summers and cold, dry winters. The mean annual rainfall in this region ranges between 650 and 750 mm mainly received between October and April. The soils formed from the extensive weathering of Beaufort shale and mudstone-sedimentary rocks with substantial sandy contributions from the Elliot, Molteno, and Clarens formations (Le Roux et al. 2010).

At both the Vrede and Reitz sites, three conservation agriculture (Cons) systems were selected within a 2 km radius. Additionally, for a broader management context, each site also included a conventional agriculture (Conv) system and a pasture system. The Conv system was selected as the closest neighbouring cropland based on its practice of tillage, limited or no soil organic cover, and minimal crop diversification. The pasture system, situated adjacent to the Cons systems, was grassland with no physical or chemical management. It is important to note that six replicate samples were collected per field (system) per site. Although it can be argued that six separate fields should have been selected per system (i.e., six fields for Cons 1, Cons 2, Cons 3, Conv, and pasture, respectively), this was not feasible considering the potential for large environmental and management variations between replications, threatening the interpretability of the results. For further information, please see the 'Sampling design' section.

2.2 Management Contexts

2.3 Vrede

The Cons systems, originally transitioned from conventional agriculture in 2012, were characterised by no-tillage, cash crop rotation with cover crops, livestock integration, retention of soil organic cover, and reduced synthetic fertiliser application (Table 1). Cash crops included maize and soybean, which were rotated with summer cover crops (SCCs) and winter cover crops (WCC). Maize synthetic fertilisation was 60 Kg ha^{-1} nitrogen (N), 14 Kg ha^{-1} phosphorus (P), and 7 Kg ha^{-1} potassium (K) band-placed at planting for all the systems. Post-harvest, maize residues were selectively grazed by cattle. Selective grazing refers to cattle having the freedom to roam in a pasture and choose the most palatable plant species to eat. This contrasts with ultra-high density grazing, where livestock are confined to a small area for a short period, encouraging them to graze on all available plant species to ensure uniform utilisation of the vegetation. The SCC and WCC received no fertilisation and were selectively grazed towards the end of the respective growing seasons. On these systems grazing continued until a minimum of 30% soil cover remained.

The Conv system received higher amounts of inorganic fertilizer and was under conventional tillage (i.e., seasonal ploughing and seedbed preparation) and continuous soybean-maize rotation. Maize synthetic fertilisation included 115 Kg ha^{-1} N, 24 Kg ha^{-1} P, and 12 Kg ha^{-1} K, which are typical fertiliser application rates for dryland maize in the region. Soybean was fertilised with 15 Kg ha^{-1} P. Post-harvest cash crop residues in the Conv system were grazed by sheep until fully utilised. Finally, the pasture system was grazed by cattle once per year during the summer growing season.

2.3.1 Reitz

The Conv systems were transitioned from conventional agriculture in 2009. Since then, a rotation of soybean, wheat, sunflower (sometimes followed by volunteer wheat), and maize was implemented (Table 2). Furthermore, reduced fertilisation, no-tillage, and organic material retention was implemented. While varying rates of fertiliser were applied on soybean, wheat and maize, sunflower synthetic fertilisation consisted of 32 Kg ha^{-1} N and 22 Kg ha^{-1} P. Also, the soybean, wheat, and maize residues were selectively grazed by cattle.

In turn, the Conv system primarily featured maize monocropping, with the 2018/19 growing season marking the first instance of soybean cultivation in more than 10 years. The

Table 1 Management context (practices) per season associated with the studied conservation agriculture, conventional agriculture, and pasture systems at Vrede

		Summer (2017/18)	Winter (2018)	Summer (2018/19)	Winter (2019)	Summer (2019/20)
Conservation Agriculture 1	**Crop (cultivar)**	Maize	N/A	Soybean	WCC**	SCC*
	Fertilisation (Kg ha^{-1})	60 N+14 P+7 K	N/A	N/A	N/A	N/A
	Grazing	Cattle (residues)	N/A	N/A	Cattle	Cattle
Conservation Agriculture 2	**Crop (cultivar)**	SCC*	N/A	Soybean	WCC**	Maize
	Fertilisation (Kg ha^{-1})	N/A	N/A	N/A	N/A	60 N+14 P+7 K
	Grazing	Cattle	N/A	N/A	Cattle	Cattle (residues)
Conservation Agriculture 3	**Crop (cultivar)**	Maize	N/A	Soybean	WCC**	SCC*
	Fertilisation (Kg ha^{-1})	60 N+14 P+7 K	N/A	N/A	N/A	N/A
	Grazing	Cattle (residues)	N/A	N/A	Cattle	Cattle
Conventional Agriculture	**Crop (cultivar)**	Maize	N/A	Soybean	N/A	Maize
	Fertilisation (Kg ha^{-1})	115 N+24 P+12 K	N/A	15 P	N/A	115 N+24 P+12 K
	Grazing	Cattle (residues)	N/A	Sheep	N/A	Cattle (residues)
Pasture	**Crop (cultivar)**	Grassland	Grassland	Grassland	Grassland	Grassland
	Fertilisation (Kg ha^{-1})	N/A	N/A	N/A	N/A	N/A
	Grazing	Cattle	N/A	Cattle	N/A	Cattle

*4 Kg ha^{-1} sorghum (*Sorghum bicolor*), 2 Kg ha^{-1} pearl millet (*Pennisetum glaucum*), 10 Kg ha^{-1} cowpea (*Vigna unguiculata*), 4 Kg ha^{-1} dolichos (*Lablab purpureus*), 3 Kg ha^{-1} sunn hemp (*Crotalaria juncea*), 1 Kg ha^{-1} radish (*Raphanus sativus*), 4 Kg ha^{-1} oat (*Avena sativa*), and 4 Kg ha^{-1} buckwheat (*Fagopyrum esculentum*)

**20 Kg ha^{-1} oat (*Avena sativa*), 8 Kg ha^{-1} rye (*Secale cereale*), 1 Kg ha^{-1} radish (*Raphanus sativus*), 3 Kg ha^{-1} vetch (*Vicia* sp.), and 0.5 Kg ha^{-1} turnip (*Brassica rapa*)

The first sampling occurred in September 2019, preceding the 2019/20 summer growing season, while the second sampling was conducted in February 2020, during the ongoing growing season. Abbreviations: nitrogen (N), phosphorus (P), potassium (K), winter cover crops (WCC), and summer cover crops (SCC)

Table 2 Management context (practices) per season associated with the studied conservation agriculture, conventional agriculture, and pasture systems at Reitz

		Summer (2017/18)	Winter (2018)	Summer (2018/19)	Winter (2019)	Summer (2019/20)
Conservation Agriculture 1	**Crop (cultivar)**	Soybean	Wheat	Sunflower	Volunteer wheat	Maize
	Fertilisation (Kg ha^{-1})	16 N+21 K	19 N+28 K	32 N+22 P	N/A	31 N+17 P+45 K
	Grazing	Cattle (residues)	N/A	N/A	N/A	Cattle (residues)
Conservation Agriculture 2	**Crop (cultivar)**	Soybean	Wheat	Sunflower	Volunteer wheat	Maize
	Fertilisation (Kg ha^{-1})	16 N+32 K	24 N+25 P+8 K	32 N+22 P	N/A	24 N+17 P+45 K
	Grazing	Cattle (residues)	Cattle	N/A	N/A	Cattle (residues)
Conservation Agriculture 3	**Crop (cultivar)**	Soybean	Wheat	Sunflower	Volunteer wheat	Maize
	Fertilisation (Kg ha^{-1})	24 N+16 P	22 N+22 P+4 K	32 N+22 P	N/A	24 N+17 P
	Grazing	Cattle (residues)	Cattle	N/A	N/A	Cattle (residues)
Conventional Agriculture	**Crop (cultivar)**	Maize	N/A	Soybean	N/A	Maize
	Fertilisation (Kg ha^{-1})	110 N+30 P+30 K	N/A	15 P+20 K	N/A	110 N+30 P+30 K
	Grazing	Cattle (residues)	N/A	Cattle (residues)	N/A	Cattle (residues)
Pasture	**Crop (cultivar)**	Grassland	Grassland	Grassland	Grassland	Grassland
	Fertilisation (Kg ha^{-1})	N/A	N/A	N/A	N/A	N/A
	Grazing	Cattle (UHDG)	N/A	Cattle (UHDG)	N/A	Cattle (UHDG)

The first sampling occurred in September 2019, preceding the 2019/20 summer growing season, while the second sampling was conducted in February 2020, during the ongoing growing season. Abbreviations: nitrogen (N), phosphorus (P), potassium (K), and ultra-high density grazing (UHDG)

Conv system is associated with conventional tillage, where the soil is intensively tilled for weed management and seed bed preparation. These fields were first ripped to a depth of 300 mm, then disced prior to planting. Soybean synthetic fertilisation consisted of 15 Kg ha^{-1} P and 20 Kg ha^{-1} K and maize fertilisation of 110 Kg ha^{-1} N, 30 Kg ha^{-1} P, and 30 Kg ha^{-1} K, also typical application rates for the region. The maize and soybean residues were selectively grazed by cattle. Finally, the pasture system was ultra-high density grazed by cattle once per year during the summer growing season. While the ultra-high density grazing stocking rate was 1 animal per 1 ha, the general stocking rate for selective grazing in the region is 1 animal per 4 ha.

2.4 Sampling Design

Conforming with industry standards, soil samples were collected before planting and during the growing season. Pre-planting sampling is routinely used for assessing soil fertility and informing fertilisation strategies (Olfs et al. 2005). Additionally, sampling during the growing season is important as it reflects the dynamic effects of crop activity on soil health (Martin and Sprunger 2022). Therefore, the first sampling interval took place in September 2019, prior to the start of the 2019/20 summer growing season, while the second sampling interval occurred in February 2020, during the growing season and after fertilisation. During this time, maize was in the R3/R4 stage and sunflower near physiological maturity. Cover crops were in the pre-flowering stage.

In each system, six plots measuring 50 × 50 m were arranged within a 100 × 150-meter grid, facilitating uniform comparisons across sites, systems, and time intervals. Each plot served as a replicate with a georeferenced point per plot selected following the unaligned grid sampling approach (Peters et al. 2007). Ten sub-samples were randomly collected within a 5-meter radius of the georeferenced point using a soil auger. The top 20 cm of soil was sampled after the mulch layer (if present) was carefully removed. These sub-samples were mixed to form a composite sample. From this composite, two 500 g aliquots were prepared: one for ecological and the other for physico-chemical analysis. To protect the integrity of the samples, they were kept away from direct sunlight and transported to North-West University (NWU) in insulated containers. Samples were stored at 10 °C and processed within 10 days of collection.

This sampling design was chosen to enable a thorough and accurate comparison within the constraints of real-world agricultural conditions, as opposed to controlled scientific trials. This approach allows for a detailed assessment of smaller, well-defined areas within larger fields, facilitating precise comparisons across different management and environmental contexts. Working within operational crop fields imposes unique challenges and limitations on experimental design; thus, our methodology is tailored to balance scientific rigor with practical feasibility. The selection of multiple, discrete plots per field aims to capture the inherent variability within these agricultural systems, providing a more nuanced understanding of soil ecosystem status under agricultural conditions.

2.5 Sample Analysis

2.5.1 Ecological Indicators

The ecological indicators of soil ecosystem status included nematode-based indices (NBIs) measuring soil ecosystem health (Maturity Index) (Bongers 1990), food web status (Enrichment, Structure, Channel, and Basal indices) (Ferris et al. 2001), and ecosystem functioning (Metabolic Footprints, namely the Composite, Enrichment, Structure, Herbivore, Bacterivore, Fungivore, Predator, and Omnivore footprints). The metabolic footprints reflect the magnitude of ecosystem functions performed by key constituents of the soil ecosystem (Ferris 2010).

Nematodes were extracted from a 200 g aliquot using the decanting-and-sieving method followed by sugar flotation method (Marais et al. 2017). The total number of nematodes per sample was counted using a De Grisse counting dish after which extracted nematodes were fixed in 4% formaldehyde and mounted on mass slides (Van Bezooijen 2006). For each slide, the first 100 nematodes were identified to genus or family level using a Nikon Eclipse 50i light microscope with 40-1000x magnification. The identified nematode counts per taxon were extrapolated to represent the total community of nematodes in the sample. Nematode-based indices were based on community data and calculated using the NINJA online tool (Sieriebriennikov et al. 2014).

Additional ecological indicators included organic matter content, permanganate-oxidizable carbon (POXC), and soil respiration. Organic matter was quantified as a measure of the accumulation of biotic-derived substances using the loss-on-ignition method (Donkin 1991). In turn, POXC represented a more processed pool of carbon, which has been shown to reflect early indicators of carbon stabilisation (Hurisso et al. 2016; Sprunger et al. 2020; Woodings and Margenot 2023) and was assessed following Moebius-Clune et al. (2016a, b). Finally, soil respiration, a measure to gauge microbial activity, was analysed using a MiniCube CO_2 meter (Haney et al. 2018).

2.6 Physico-Chemical Properties

Physico-chemical properties measured in this study included particle size distribution (i.e., fractions of sand, silt, and clay), $pH_{(H2O)}$, electrical conductivity (EC), and macro [inorganic N, Mehlich III extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and sulphur (S)] and micro [Mehlich III extractable, boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn)] nutrients. The particle size distribution was determined using Cornell's soil texture method (Schindelbeck et al. 2016), while pH and EC were measured in a 1:2.5 water extract using a Hanna HI 9811-5 pH/EC meter (Non-affiliated_Soil_Analysis_Work_Committee 1990). Inorganic N was determined as the sum of nitrate and ammonium, which were extracted using 1 M potassium chloride (KCl) solution (Keeney and Nelson 1983) and analysed using an Auto Analyzer Flow system. The Mehlich III test was performed by the Intertek Laboratories (Elandsfontein, South Africa) using Inductively Coupled Plasma Optical Emission spectroscopy (ICP-OES) for nutrient quantification (Mehlich 1984).

2.7 Statistical Analysis

A multivariate approach was designed to evaluate the influences of agricultural systems over sampling intervals on selected indicators of soil ecosystem status, for two distinct management and environmental contexts: Vrede and Reitz. Five levels of agricultural systems (Cons 1, Cons 2, Cons 3, Conv, and pasture) and two levels of sampling intervals (first and second) were considered as predictive variables. The ecological indicators were log-transformed [log(x + 1)] and normalised to attenuate the non-normality of distribution, as confirmed by the Shapiro-Wilk test at a 5% significance level.

The statistical methods employed, including Permutational Multivariate Analyses of Variance (PERMANOVAs) and constrained Canonical Analyses of Principal Coordinates (CAPs), were selected due to their robustness in handling complex, multivariate ecological data. This approach facilitated the evaluation of multiple factors and their interactions simultaneously, providing a comprehensive view of how the agricultural systems and sampling intervals affected soil ecosystems. The CAP was utilised to spatially organise the data, focusing on the "Agricultural System x Sampling Interval" factor for grouping. The biplots ordination of the CAP analyses helped to visualise the complex relationships within the data, simplifying interpretation by reducing dimensionality while preserving patterns associated with the interactions of interest. Furthermore, the correlation between the CAP axes and each ecological indicator was examined to identify the primary indicators driving the variation in the dataset. Indicators with a Pearson correlation coefficient greater than 0.6 or less than −0.6, in relation to the CAP axes, were identified as primary indicators. Similarly, the measured physico-chemical properties were depicted as vectors overlaid on the ecological ordination to elucidate their associations with ecological variations. Physico-chemical properties with Pearson correlation coefficients exceeding 0.6 or below −0.6 were also designated as primary variables.

Subsequent analyses involved pairwise comparisons of each primary ecological indicator and physico-chemical property at a 5% significance level, again considering the interaction between "Agricultural Systems x Sampling Intervals".

Table 3 Permutational Multivariate Analysis of Variance (PERMANOVA) of the predictive variables (systems and intervals) and their interaction for selected indicators of soil ecosystem status recorded at Vrede

	df	SS	MS	Pseudo-F	*P*(perm)
Systems	4	336,5	84,1	9,6	**< 0,0001**
Intervals	1	92,9	92,9	10,64	**< 0,0001**
Systems x Intervals	4	75,6	18,9	2,2	**< 0,01**
Res	50	439,1	8,8		

3 Results

3.1 Vrede

The PERMANOVA analysis revealed a significant interaction ($p = 0.0034$) in the ecological indicators between the systems and intervals (Table 3). Furthermore, the primary ecological indicators responsible for the evidenced variation in the CAP analysis included organic matter (-0.91 r with CAP 1), soil respiration (-0.85 r with CAP 1), Maturity Index (-0.65 r with CAP 1), Composite Footprint (-0.73 r with CAP 2), Channel Index (0.72 r with CAP 2), and Bacterivore Footprint (-0.71 r with CAP 2) (Table A.1).

These ecological indicators promoted a partial grouping of samples according to the systems and intervals (Fig. 1). This was most evident for the pasture system, which generally presented the highest values, during both intervals, of organic matter (Fig. 2a), soil respiration (Fig. 2b), and the Maturity Index (Fig. 2c). The grouping of the Cons and Conv systems was somewhat less clear, except for an evident separation between sampling intervals mainly driven by the Channel Index and Composite and Bacterivore footprints. In the Cons 2, Cons 3, and Conv systems, the Channel Index was significantly higher during the second sampling interval (Fig. 2d). Conversely, the first sampling interval presented significantly higher Composite Footprint values in both the

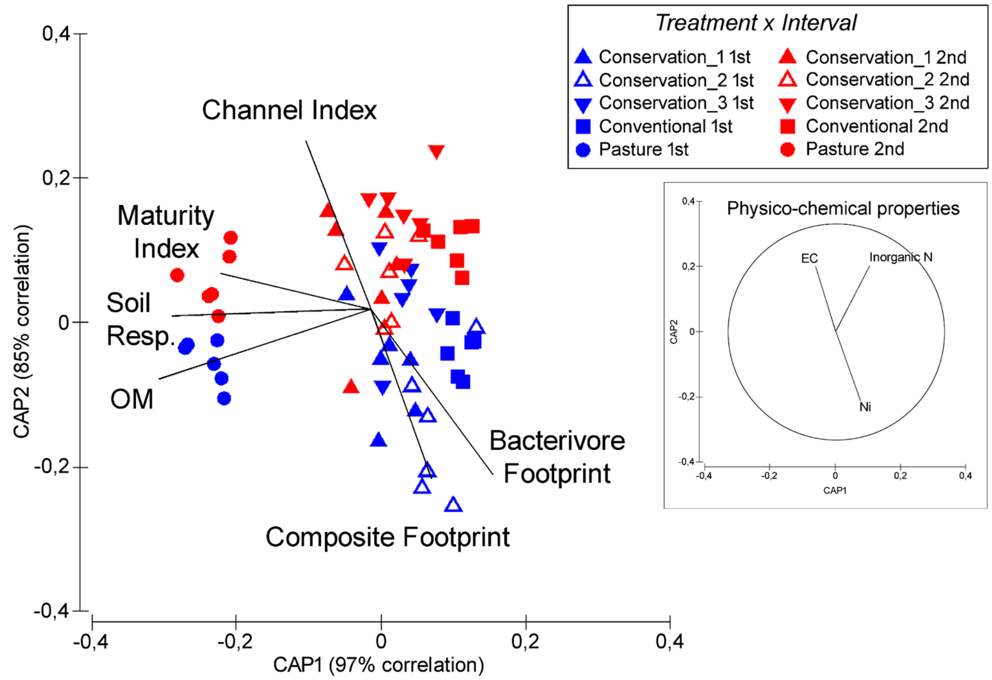

Fig. 1 Ordination of Canonical Analysis of Principal Coordinates (CAP) showcasing the distribution of evaluated ecological indicators at Vrede. Vectors on the primary ordination represent ecological indicators that exhibit a Pearson correlation coefficient (r) with CAP axes 1 or 2 of ±0.6 or greater. Similarly, physico-chemical properties correlating with the CAP axes are presented on an overlay graph. Abbreviations: Soil respiration (Soil Resp.) and organic matter (OM)

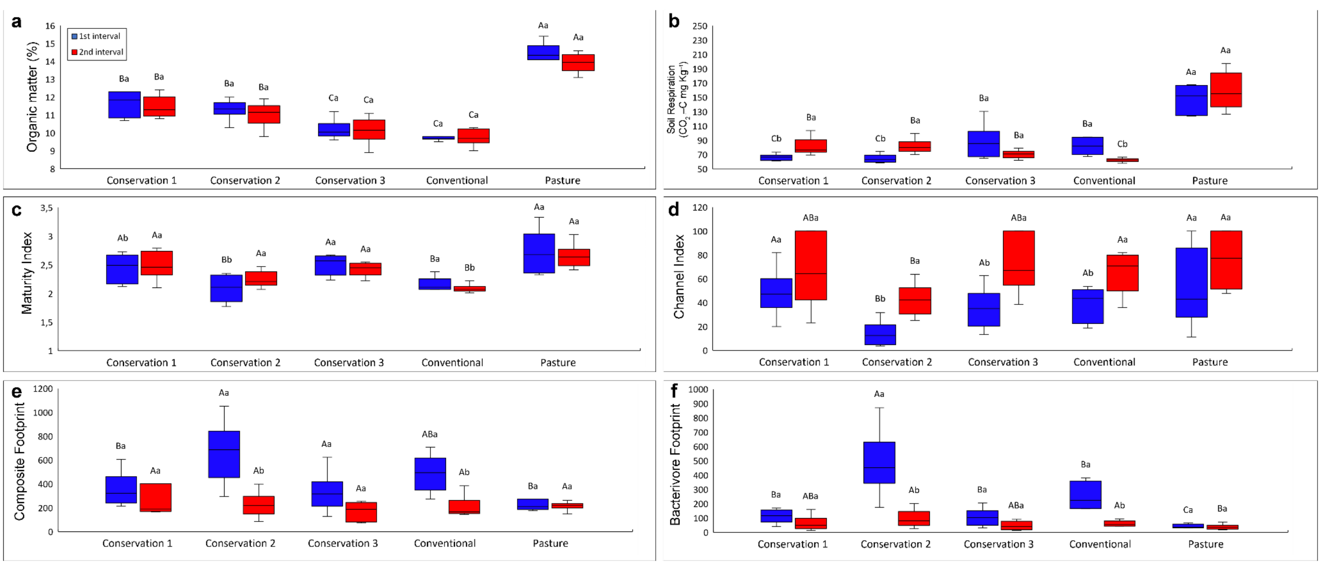

Fig. 2 Pairwise comparisons of the primary ecological properties recorded at Vrede, namely (**a**) organic matter, (**b**) soil respiration (CO_2-C), (**c**) Maturity Index, (**d**) Channel Index, (**e**) Composite Footprint, and (**f**) Bacterivore Footprint. Comparisons were made between agricultural systems (conservation 1–3, conventional, and pasture) and sampling intervals (September 2019 = blue boxes; February 2020 = red boxes). Significant differences ($p < 0.05$) between systems are indicated with uppercase letters, while significant differences ($p < 0.05$) between intervals are indicated with lowercase letters

Cons 2 and Conv systems (Fig. 2e). Similarly, significantly higher Bacterivore Footprint values were recorded during the first sampling interval at Cons 2 and Conv (Fig. 2f).

Correlating physico-chemical properties with the CAP axes revealed that Ni (-0.63 r with CAP 2), Inorganic N (0.6 r with CAP 2), and EC (0.6 r with CAP 2) were the primary properties associated with the ecological variation (Table A.2). Inorganic N was associated with the crop production systems (Fig. 1) but was generally significantly higher at the Conv system during both intervals (Fig. A.1a). In turn, EC was significantly higher (except at Cons 1) during the second sampling interval (Fig. A.1b). Finally, Ni was significantly higher during the first sampling interval in Cons 2, and significantly higher when comparing this system to the remaining systems during both sampling intervals (Fig. A.1c).

Table 4 Permutational Multivariate Analysis of Variance (PERMANOVA) of the predictive variables (systems and intervals) and their interaction for selected indicators of soil ecosystem status recorded at Reitz

	df	SS	MS	Pseudo-F	*P*(perm)
Systems	4	317,8	79,4	8,5	**<0,0001**
Intervals	1	44,1	44,1	4,7	**<0,0001**
Systems x Intervals	4	113,6	28,4	3,1	**<0,0001**
Res	50	468,6	9,4		

3.2 Reitz

Similarly to Vrede, there was a significant interaction ($p = 0.0001$; Table 4) between the systems and intervals in the Reitz data. The primary ecological indicators responsible for the variation in the CAP analysis included organic matter content (0.90 r with CAP1), POCX (0.76 r with CAP1), and soil respiration (0.73 r with CAP1) with the Herbivore Footprint (0.63 r with CAP1 and 0.61 r with CAP2) being the only NBI recorded as a primary indicator (Table B.1).

The CAP biplot revealed that the Cons 1 system clearly grouped (during both intervals) and presented the lowest values of the primary ecological indicators when compared to the remaining systems (Fig. 3). Pairwise comparisons confirmed that Cons 1 overall had the lowest values of organic matter (Fig. 4a), POXC (Fig. 4b), and soil respiration (Fig. 4c). Conversely, Cons 3 exhibited the highest values for these ecological indicators, except for POXC, where the highest values were observed in the pasture system. There was minimal variation between the sampling intervals with no recorded significant differences for organic matter, POXC, and soil respiration. However, the Herbivore Footprint did not conform to this trend with most of the systems presenting significant differences between sampling intervals (Fig. 4d).

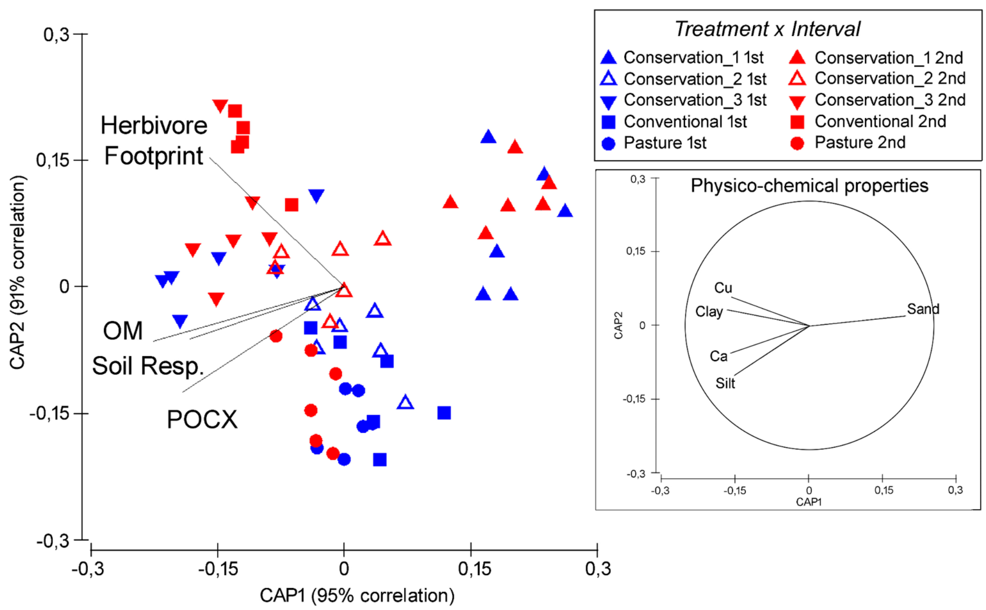

Fig. 3 Ordination of Canonical Analysis of Principal Coordinates (CAP) showcasing the distribution of evaluated ecological indicators at Reitz. Vectors on the primary ordination represent ecological indicators that exhibit a Pearson correlation coefficient (r) with CAP axes 1 or 2 of ±0.6 or greater. Similarly, physico-chemical properties correlating with the CAP axes are presented on an overlay graph. Abbreviations: Soil respiration (Soil Resp.), organic matter (OM), and permanganate-oxidizable carbon (POXC)

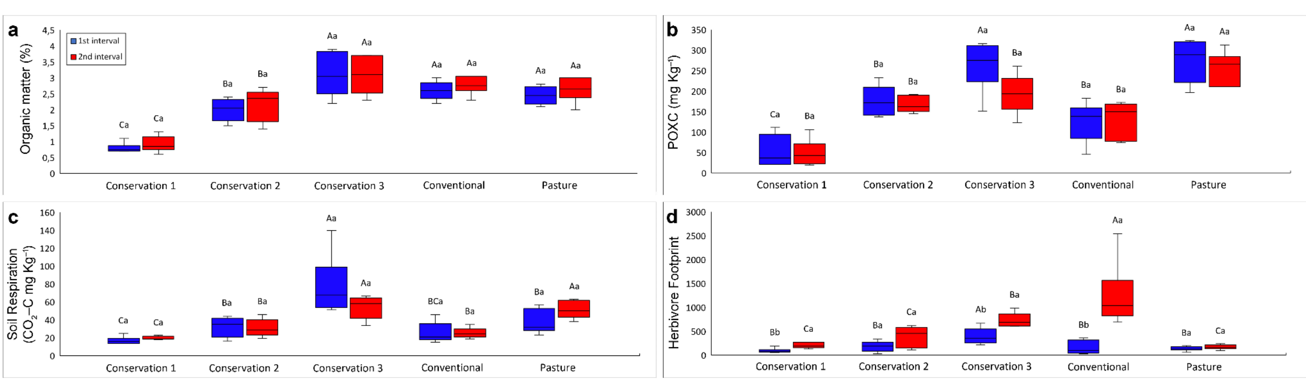

Fig. 4 Pairwise comparisons of the primary ecological properties recorded at Reitz, namely (**a**) organic matter, (**b**) permanganate-oxidizable carbon (POXC), (**c**) soil respiration (CO_2-C), and (**d**) Herbivore Footprint. Comparisons were made between agricultural systems (conservation 1–3, conventional, and pasture) and sampling intervals (September 2019 = blue boxes; February 2020 = red boxes). Significant differences ($p < 0.05$) between systems are indicated with uppercase letters, while significant differences ($p < 0.05$) between intervals are indicated with lowercase letters

Several physico-chemical properties presented strong correlations with the ecological indicator data. This included sand (-0.77 r with CAP 1), clay (0.67 r with CAP 1), Ca (0.64 r with CAP 1), Cu (0.63 r with CAP 1), and silt (0.61 r with CAP 1) (Table B.2). While sand was positively correlated to Cons 1, the remaining primary physico-chemical properties were positively correlated with the Cons 2, Cons 3, Conv, and pasture systems (Fig. 3). The pairwise comparisons confirmed that sand (Fig B.1a) was significantly higher and silt (Fig B.1b) and clay (Fig B.1c) significantly lower at Cons 1 during both sampling intervals. Clay and silt were the highest at Cons 3 and Cons 2, respectively. Calcium was also significantly lower at Cons 1 during both sampling intervals (Fig B.1d), while Cu was significantly higher at the Cons 3 and Conv systems (Fig B.1e).

4 Discussion

The marked variability in ecological indicators between study sites, management systems, and across sampling intervals highlights the potential complexity and heterogeneity of soil ecosystems in different agricultural settings (Trivedi et al. 2016; Wilhelm et al. 2023). At Vrede, the elevated soil ecosystem status of the pasture system likely stemmed from continuous organic cover and minimal disturbance, factors known to result in higher levels of organic matter and POXC content (Augarten et al. 2023; Du Preez et al. 2024). These conditions can promote soil ecosystem functioning as evidenced by substantially higher respiration rates, indicating greater microbial activity (Haney et al. 2018). Furthermore, the pasture system also presented greater Maturity Index values indicating the presence of more sensitive nematode indicator taxa and a healthier soil ecosystem (Bongers 1990; Du Preez et al. 2022). While the pasture system at Vrede demonstrated strong ecosystem health, the performance of the Cons systems also warrants attention.

The higher Maturity Index values in the Cons systems compared against the Conv system suggest the potential of conservation agriculture to bolster soil ecosystem health. Practices like no-tillage and the integration of cover crops are known to increase organic matter (Breil et al. 2023; Wulanningtyas et al. 2021) and promote soil biodiversity (Sapkota et al. 2012; Schmidt et al. 2018), thereby supporting the health and functioning of soil ecosystems. Finally, lower inorganic N levels in the Cons systems correspond with reduced fertilisation, which is promoted as a good agricultural practice in support of conservation agriculture outcomes (Kassam et al. 2014; Thierfelder et al. 2018). However, the reason for distinct differences observed in the Channel Index and Composite and Bacterivore footprints across different intervals remains unknown. Higher Channel Index values, noted during the second sampling interval, suggest fungal-dominated decomposition pathways, as indicated by increased numbers of fungivore nematodes (Du Preez et al. 2022; Ferris et al. 2001). This explains, at least in part, the elevated Bacterivore Footprint observed during the first sampling interval, which corresponds with lower abundances of fungivore nematodes. At Vrede, the main factor driving ecological differentiation between systems appeared to be the management context.

In contrast, Reitz presented greater discrepancies between the Cons systems, with both good and poor performing soil ecosystems. This suggests that specific management practices or varying environmental context at field level may be responsible for these differences. From a management perspective, the primary distinction between Cons 3 and Cons 1 was the amount of fertiliser applied across cultivation periods during the production of soybean, wheat, and maize. However, since these differences were small and no major nutrient parameters (N, P, K) were identified as key drivers, it is unlikely that fertilisation explains the observed variation in ecosystem status. Notably, the higher Herbivore Footprint in the Conv system during the second sampling interval is likely due to the presence of maize, a viable host crop that promotes the proliferation of nematode pests (Maina et al. 2019). In contrast, the pasture system, a natural, biodiverse grassland, presented substantially lower Herbivore Footprints, likely due to its ability to regulate pests and diseases more effectively (Creamer et al. 2022; Mitchell et al. 2002; Paudel et al. 2021).

While management practices may have influenced certain ecological indicators at Reitz, these factors alone do not fully explain the observed variation in ecosystem status. Environmental context, particularly physico-chemical soil properties, played an important role in determining the ecological status of the Reitz agricultural systems. Ecological indicators including organic matter, POXC, and soil respiration were clearly influenced especially by soil texture, which has well-documented effects on soil biological, chemical, and physical properties (Fine et al. 2017). For example, it has long been established that percent clay is a major driver of soil organic matter content (Krause et al. 2018). The adsorption of organic matter onto clay minerals contributes to the physical preservation of organic matter by minimising its exposure to decomposing microorganisms (Six et al. 2000). It is widely accepted that the retention of organic matter is positively correlated with the decreasing size of the soil fractions (Dungait et al. 2012; Soinne et al. 2020). Thus, it is not surprising that fine textured soils consistently have greater POXC values relative to medium and course textured soils (Fine et al. 2017; O'Neill et al. 2021). A study exploring soil health properties across the Midwest, USA found that texture class accounted for over 60% of the variation and had a much larger effect on soil properties relative to agricultural management (Sprunger et al. 2021).

Differences in soil texture between Vrede and Reitz likely also influenced management effects on various soil properties. For example, pasture management at Vrede seemed to increase soil respiration compared to the other agricultural systems. In contrast, respiration values were similar across most of the treatments at Reitz. Lower soil respiration values at Reitz are likely the result of lower overall ecosystem status, including lower organic matter and high sand content relative to the high clay content and greater organic matter values found at Vrede. This suggests that while conservation agriculture systems and pasture management can elevate certain soil health properties, underlying soil texture is likely the main driver of ecosystem status.

These findings emphasise that the variability in and status of soil properties must be assessed before specific management practices for farmers are designed (Lal 2020; Strauss et al. 2021). This is to identify specific problems and solutions related to soil ecosystem health and functioning at the start of a long-term soil health strategy. Local and global solutions should be considered to create a context-specific soil health strategy, but the implementation approach should be dynamic and aimed at the continuous adaptation of agricultural systems under unique local contexts. In support of this approach, Smith et al. (2021) described results and experiences from various participatory, on-farm research initiatives that used farmers as key innovators, which led to an acceleration in the adoption and adaptation of new production systems.

Smith et al. (2021) found that the impact of CA practices on soil health was influenced by the quality and duration that they were applied, which were in turn determined by the innovation capacity of the farmer (i.e. the ability of the farmer to test, reflect on and integrate these principles in an adaptive management approach). Secondly, the environmental context of the farm also influenced the rate of soil health restoration. For example, in the western crop production regions of South Africa, low soil organic carbon levels are to a large degree related to lower rainfall, high drought risk, and high evapotranspiration. These factors limit crop growth, thereby reducing carbon inputs from plant residues that are critical for soil organic carbon buildup. Furthermore, the inherent low fertility of sandy soils in these regions, intensifies the situation hindering nutrient retention and cycling, while also making these soils more susceptible to wind erosion and subsurface compaction (Du Preez et al. 2011; Swanepoel and Tshuma 2017). Addressing these challenges requires adopting management practices such as deep ripping, mulch retention (Laker and Nortjé 2024), integrated soil fertility management using blends of biological and chemical fertilisers, and incorporating cover crops and livestock rotations (Mitchell et al. 2024). However, it is important to have a long-term view of at least 10 years and more, to be able to properly evaluate and adapt appropriate local conservation agriculture systems (Smith et al. 2021). The inclusion of multi-specie cover crops in rotation with cash crops will help to produce the below- and above-ground biomass (Pisarčik et al. 2024; Wong et al. 2024). This is known to increase biodiversity and stimulate soil ecological functioning (Mitchell et al. 2024; Opoku et al. 2024). Livestock integration on the cover crops further increase the impact on soil fertility, soil organic carbon sequestration, financial and income stability, and increased profits (Strauss et al. 2021).

A promising complementary approach is the gradual integration of biological products, which have the potential to reduce synthetic fertiliser inputs (Bargaz et al. 2018; Shah et al. 2021). However, it is important to acknowledge that biological products cannot fully replace synthetic fertilizers at present (Bargaz et al. 2018; Shah et al. 2021) as their effectiveness is largely dependent on site-specific factors, particularly soil organic matter levels and nutrient reserves. For example, in soils with low organic matter and limited nutrient reserves, mineralisation processes may fail to release sufficient plant-available nutrients to meet the demands of high-nutrient-requiring crops such as maize (Whalen 2014). Furthermore, the adoption of biological products to restore soil ecosystem functions have shown sharp upsurges locally and globally, but with mixed levels of success (Garbowski et al. 2023; Tshuma et al. 2024). Smith et al. (2022) showed that the success of these strategies aiming to adopt and adapt new context specific practices and technologies depends on careful assessment, planning, design, implementation, and management. It is recommended that farmers should start on a small scale (around 10% of your land), adopting a continuous trial-and-error approach, which is informed by a rigorous monitoring and evaluation process (including relevant indicators discussed in this article, comparing different options and trade-offs) (Smith et al. 2022).

5 Conclusions

This study adds to the growing body of evidence highlighting the importance of agricultural management and environmental contexts in the successful implementation of conservation agriculture systems. However, our findings suggest that the environmental context, in this study mainly reflected as soil texture, may have a substantial impact on soil ecosystem status, potentially outweighing the effect of the management system itself. This underscores the necessity of setting realistic expectations for the outcomes of conservation and other agricultural systems based on the inherent potential of the local environment.

To promote soil ecosystem health and ultimately soil health, it is important to focus on agricultural systems that sequester and store carbon in farmland soils. Increased carbon promotes biological activity, improve water regulation, and facilitate nutrient cycling, among other benefits. Our study also reaffirms the importance of considering the timing of soil sampling in any soil health monitoring program, as temporal variations can substantially influence the observed ecological indicators.

In conclusion, for the successful implementation of conservation agriculture systems, a highly adaptive on-farm innovation approach should be followed considering unique farmer contexts. In this process, farmers play a central role, while they are joined and supported by other key stakeholders, such as researchers, and informed by a well-designed monitoring and evaluation process.

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Declarations

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