Soil organic amendments for climate-smart agriculture

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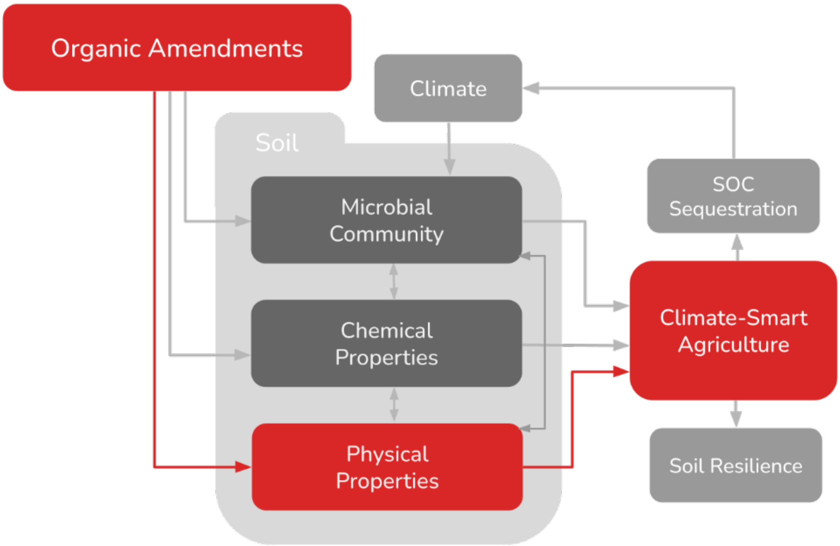
Organic Amendments
Climate
Soil
Microbial Community
Chemical Properties
Physical Properties
SOC Sequestration
Climate-Smart Agriculture
Soil Resilience

CHAPTER 5

Temporal Variability in Organic Amendment Impacts on Hydro-Physical Properties of Sandy Agricultural Soils

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ABSTRACT

Organic amendments (OAs) can improve the hydro-physical properties of a soil and thereby potentially enhance the resilience of agricultural systems to droughts and floods. An OA's contribution to this resilience, however, depends on the timeliness of its impacts, as soil improvements should be achieved when droughts are most frequent or flood risks are greatest. Yet little is known regarding the temporal variability of OA impacts or the influence of OA quantity and quality thereupon. In this research, therefore, we investigated at two agricultural sites the temporal variability of improvements in soil bulk density, aggregate stability, infiltration capacity and water retention after the application of compost, farmyard manure, bokashi, a selection of organic residues from landscape maintenance and a combination of these residues with manure. Results showed that, depending on management practices and soil type, OAs decrease bulk density by up to 9.8%, increase infiltration capacity by up to 108.1%, aggregate stability by up to 60.0% and water retention by up to 77.8% relative to unamended controls within three years of repeated application. However, the magnitude of these improvements varies up to 96% between seasons, depending on the soil property and OA treatment. On average, for all treatments, impacts relative to the control varied between different seasons by 5% for bulk density, 47.1% for infiltration capacity, 22.6% for aggregate stability and 26.3% for water retention. When offsetting OA nutrient differences with mineral fertilizers, this variability showed a stronger correlation to differences in OA application quantity than quality (i.e. chemical composition). Results suggest that disregarding temporal variability in OA impacts can result in an inaccurate valuation of OAs as either effective or ineffective in improving soil resilience, given that impacts may, instead of their frequently presumed persistency, actually be highly transient or lagged. Our findings highlight the importance of considering the potential intra-annual variability of OA impacts on soil hydro-physical properties when designing OA application strategies to ameliorate the effects of specific seasonal climatic challenges.

Key words: *aggregate stability; bulk density; infiltration capacity; soil management; water retention; compost; manure; bokashi*

5.1 INTRODUCTION

Future agricultural production will be challenged by the intensification of seasonal precipitation extremes due to onsetting climate change (IPCC et al. 2021). Due to this, much of the world will experience decreases in the number of summer precipitation events and strong increases in winter precipitation intensity (Donat et al. 2013; Giorgi, Coppola, and Raffaele 2014; IPCC et al. 2021). These climate change effects can hamper agricultural production by exposing it to flooding and droughts. Agricultural soils might be particularly vulnerable, as they often suffer from reduced infiltration capacity and water retention due to their degradation under conventional cultivation practices (Bai et al. n.d.; Karlen and Rice 2015; Lal 2012). Rehabilitating agricultural soils and improving their hydro-physical properties may thus be necessary to improve the resilience of our food production systems to a changing climate (Cornelis, Waweru, and Araya 2019).

Organic amendments (OAs) can improve soil hydro-physical properties and thereby potentially enhance the climate resilience of our crop production systems (Diacono and Montemurro 2011; Larney and Angers 2012; Montgomery 2007). Different OAs have demonstrably improved soil hydraulic and physical properties such as bulk density (Cercioglu 2017; García-Orenes et al. 2005; Khaleel et al. 1981; Reynolds et al. 2009; Tejada and Gonzalez 2008), infiltration capacity and hydraulic conductivity (Eusufzai and Fujii 2012; Meena et al. 2020; Wanniarachchi et al. 2019), penetration resistance (Celik, Ortas, and Kilic 2004; Negiş et al. 2020), pore size distribution (Luna et al. 2018), aggregate stability (Abiven et al. 2009; Albiach et al. 2001; Annabi et al. 2011; Metzger, Levanon, and Mingelgrin 1987), and water retention (Ankenbauer and Loheide 2017; Eden et al. 2017; Meena et al. 2020; Rawls et al. 2003; Zhou et al. 2020). Such improvements may support crop productivity as well as buffer climate change impacts. For instance, the roots of crops grown on soils of lower bulk densities more easily penetrate the soil and benefit from improved oxygen diffusion into the rhizosphere (Valentine et al. 2012); soils in which water readily infiltrates are less susceptible to ponding and land degradation by runoff (Hueso-González et al. 2015); soils capable of retaining more water provide crops with greater resilience to dry spells and lower irrigation requirements (Chambal Pandey and Sanjay Shukla 2006; Terleev et al. 2017; Zhang et al. 2006); and soils with high aggregate stability have increased nutrient retention through the occlusion of organic matter (Lutzow et al. 2006; Six et al. 2004; Tisdall and Oades 1982).

The efficacy of OAs in improving soil resilience, however, depends not only on the magnitude of improvements, but also on their intra-annual variation and persistence of impacts. Ideally, OAs improve relevant soil properties prior to the occurrence of a seasonal weather extreme. Yet little is known regarding the seasonal variability of OA impacts as most studies evaluate changes in soil properties at fixed yearly intervals (Cercioglu 2017;

Ferreras et al. 2006; Tejada and Gonzalez 2008) or once at the end of an experiment (Z. Li et al. 2018; Singh Brar et al. 2015; Yüksel and Kavdır 2020; Zhao et al. 2009). Studies that do explore short-term OA impacts observe strong seasonal fluctuations in the response of soil hydro-physical properties to applications of OAs such as compost (Castellini et al. 2022; Felton 1995), sewerage sludge (Delibacak, Okur, and Ongun 2009), and biochar (Ouyang et al. 2013). These seasonal variations can furthermore differ strongly per soil hydro-physical property (Zare, Afyuni, and Abbaspour 2010). Yet, the short-term temporal dynamics of soil hydro-physical properties - let alone OA impacts thereupon - remain generally poorly investigated (Alletto and Coquet 2009; Geris et al. 2021; Girei, Abdu, and Abdulkadir 2016; Jirků et al. 2013).

OA impacts are influenced by the quantity (i.e. application rates) and qualitative properties (i.e. chemical composition) of the OAs applied Yet, even for intensively studied changes in aggregate stability, remarkably few studies attempt to correlate OA impacts with the initial biochemical characteristics of the OAs (Abiven et al. 2009). A dedicated study to assess the short-term impacts of different OAs in a dynamic agricultural setting will contribute to deepening our understanding of the functional relationship between OAs and soil hydro-physical properties, and will be valuable for the identification of OAs that are most effective in improving the seasonal resilience of our food production systems.

In this research, therefore, we explored the intra-annual variability in the response of four prominent soil hydro-physical properties to four annual OA treatments in a three-year experiment on two agricultural soils (an anthrosol and a podzol). We monitored changes in bulk density, infiltration capacity, aggregate stability and water retention after application of compost, farmyard manure, a locally available organic residue, and a combination of manure and the above residues. Soil hydro-physical properties were measured twice per year, in the second and third year of the experiment, and analyzed for correlations with OA application rate (quantity) and composition (quality). Bulk density was only measured in the third year of the experiment. We hypothesized that, for each site, i) OA treatments result in significant improvements in soil hydro-physical properties, ii) that these improvements significantly vary between seasons for both soil types, and iii) that these improvements and their seasonal differences are related to differences in OA quantity or quality (e.g. C:N, total N, organic matter content, etc.). Based on the significance of these improvements and seasonal differences therein, we classify the impact of each OA for each soil property as either persistent, lagged, transient, or enhanced (further defined in the materials and methods section) in order to facilitate a comparison of their temporal impacts.

5.2 MATERIALS AND METHODS

5.2.1 Field Sites

The three-year experiment was carried out in the period 2018-2020. In 2018, triplicate experimental blocks were laid out at two agricultural sites of contrasting soil types in a randomized complete block design. The first site is located near Heelsum, the Netherlands (51°58'42"N, 5°45'58"E), and consists of a coarse sandy Anthrosol (WRB-FAO classification; 74% sand (coarse), 20% silt, 2% clay, 3.7% organic matter, pH 5.4). The site lies elevated in its surroundings, resulting in a deep water table (>2m), making the crops vulnerable to drought. The second site is located near Harreveld (51°59'8"N, 6°29'53"E) and is characterized as a loamy-sand Podzol (WRB-FAO classification; 72% sand (fine), 19% silt, 3% clay, 6.2% organic matter, pH 5.6), an aeolian deposition of the Pleistocene. Both sites have a history of maize (Zea mays L.) cultivation with seasonal rotation of *Lolium multiflorum* as a winter catch crop. In contrast to the Heelsum site, however, the winter catch crop at Harreveld is sown in together with the maize instead of after harvest and its maize cultivation was periodically alternated with meadow. Both sites lie within the same region and have an annual mean temperature of 10°C, with an average minimum of 0°C and maximum of 21°C, and an average annual precipitation of 825 mm for the period 1991-2020 (KNMI, 2022). An overview of the soil properties of each site is presented in Appendix O.

To create an experimental setting closest resembling agronomic reality, the farmers at both sites had agreed to manage their fields according to their own conventional practices but to stay consistent in these practices for the duration of the three-year experiment. A resulting difference between the sites is an extra tillage that occurs each year after harvest, before winter sampling, at the Anthrosol site. Its purpose was to integrate the corn stubble into the soil and plant the winter catch crop. At the Podzol site, this tillage was not necessary, as the catch crop was sown in together with the maize in spring. Other differences in site management are listed in Appendix P.

5.2.2 Organic Amendments

Four OAs were applied as treatment factors at each site: i) compost, ii) farmyard manure, iii) Bokashi or a locally available organic residue, and iv) the combination of ii and iii. For the Anthrosol site, the organic residue (iii) consisted of grasses (G) recovered from public, rural, green areas such as roadsides and parks. For the Podzol site, the organic residue (iii) consisted of waterway weeds and reeds (WWR) in the first year (not included in this study), naturally fermented WWR in the second year, and a commercial, fermented Bokashi product in the third year - varying with local availability. We included the combination treatment of manure and organic residue as it reflects a Dutch agronomic reality where organic residues are unlikely to be applied alone given the excess of manure produced by the Dutch livestock industry. The four organic treatments at each site were compared to a control treatment that did not receive any organic input. Each treatment was replicated in three 10x10 m blocks.

Application rates were determined based on the nutrient properties (N, P and K concentrations). Based on national fertilization recommendations and standard application norms (RVO 2022), we limited the total nutrient input for each treatment to 120 kg ha^{-1} available N, 50 kg ha^{-1} P_2O_5, and 200 kg ha^{-1} K_2O. Each OA was applied in maximum until one of these nutrient limits was met. These rates varied slightly year-to-year due to the small variations in OA quality of each year. On average, application rates amounted to approximately 20 tonnes ha^{-1} fresh matter for compost, 30 tonnes ha^{-1} for manure, 20 tonnes ha^{-1} for grasses, 20 ton ha^{-1} for WWR, 20 tonnes ha^{-1} for Bokashi, and 50 tonnes ha^{-1} for the mixed treatment of combined grasses or WWR with manure. To isolate as much as possible the effect of the OAs and their *organic* chemical characteristics and thus to offset as much as possible the potential effect of differences in nutrient inputs on soil properties, each plot, including the control, was supplemented with mineral fertilizers (N, P, K). This furthermore reflects a Dutch agro-industrial reality where many farmers supplement OA applications with mineral fertilizers in order to meet the maximum fertilization limits for each nutrient. The resulting wide variations in both the quantity and quality of the applied OAs were regarded as an asset, allowing a general assessment of the importance of both aspects in contributing to resulting changes in soil properties.

The OAs were mechanically integrated into the soil with a disc harrow to approximately 15 cm depth. An overview of the mineral and organic applications to each block, per year, and per site, is presented in Appendix Q. Analysis of OA chemical properties was performed by the Nutrient Management Institute B.V., Wageningen, and Eurofins Agro, Wageningen following conventional methods using predominantly elemental combustion analysis. A complete overview of the OA characteristics is presented in Appendix R.

5.2.3 Field sampling and measurements of hydro-physical soil properties

Organic amendments were applied after the harvest of the winter catch crop each year. Subsequently, maize was sown, and mineral fertilizers were applied. A full overview of the field management and sampling dates is presented in Appendix P. Infiltration capacity, aggregate stability, and water retention were measured in late June, approximately three months after sowing, and in late November, approximately three months after harvest/ploughing, in years two (2019) and three (2020) of the experiment. Soil bulk density was only sampled in late May and late November, in the final year of the experiment (2020) when OA impacts were expected to be greatest.

Bulk Density

Soil cores of 5 cm length and 5.3 cm diameter (110.3 cm^3) were inserted after carefully removing 10 cm of topsoil to recover an undisturbed soil sample spanning a depth of 10 to 15 cm. The contents of the soil cores were oven-dried at 70°C for 24h and weighed. Soil bulk density ($\boldsymbol{p_b}$) was calculated by $\boldsymbol{p_b = M_d/V}$; where $\boldsymbol{M_d}$ was the dried soil mass and $\boldsymbol{V}$ was the volume of the soil core.

Infiltration capacity

Infiltration capacity was measured *in situ* using a standard, double-ring infiltrometer. Outer (⌀55 cm) and inner (⌀30 cm) galvanized steel rings were inserted into the soil up to a depth of 10 cm. Both rings were filled to ~10 cm head, after which the change in the water level of the inner ring was recorded over time. Throughout the infiltration process, the water level of the outer ring was kept equal to that of the inner ring. Measurements were repeated until we no longer observed a significant rate of change in water level. We commenced each measurement by refilling both rings after the water level inside them had dropped to approximately 1 cm head.

Aggregate Stability

Changes in wet aggregate stability were determined following an adapted wet sieving method (International Maize and Wheat Improvement Center 2013). Triplicate soil samples were collected spanning an approximate depth of 10-17 cm, transported in closed 70 ml polypropylene containers, and air-dried for two weeks. Samples were transferred to aluminum cups and oven-dried at 60°C for 24h before sieving. The oven-dry samples were sieved at 8 mm to remove any roots, rocks and pebbles, and to break any large aggregates (>8 mm; along natural planes of weakness). A sieve stack of descending sizes (2 mm, 1 mm, 500 µm, 250 µm, and 125 µm) was then submerged into a column of water.

Approximately 20-40 grams of dry soil (M$_T$) was weighed and slowly wetted with deionized water, using a wash bottle, and gently poured onto the top of the 2 mm sieve. The sample was sieved underwater in a vertical direction for 2 minutes at a frequency of 30 waves, of 3 cm amplitude, per minute. Each sieve was subsequently washed, breaking the aggregates, and recovering the dispersed aggregate material using a hand vacuum pump and a large funnel capped with a pre-weighed, rayon polyester filter cloth (pore size of 22-25 µm). The filter with sample (M$_{Ai}$) was oven-dried at 60°C. Coarse material remaining on each sieve (M_{Ci}) was pooled for each sample and dried accordingly. The fraction of water-stable aggregates (W_{Fi}) was then calculated following (eq. 5.1):

$$W_{Fi} = \frac{\mathrm{M}_{Ai}}{\mathrm{M}_T - \sum_{i=1}^{n} \mathrm{M}_{Ci}} \tag{5.1}$$

Where i = 1,2,…,n and corresponds to each aggregate size fraction. The mean weight diameter (MWD) [mm] was calculated as an index for aggregate stability (eq. 5.2):

$$MWD = \sum_{i=1}^{n} W_{Fi} \cdot x_i \tag{5.2}$$

Where x_i is the average diameter of each size fraction (i.e., mean intersieve size), and W_{Fi} is as defined in eq. 5.1.

Water Retention

Changes in soil water retention were determined using pressure plates at the Soil Hydro-Physics lab of Wageningen University & Research. Two soil samples per treatment were extracted from 10 cm depth, one disturbed sample using a garden hand shovel and a second undisturbed sample using a 110.3 cm^3 soil core. In the laboratory, the disturbed sample was turned into sludge with demineralized water. A 20 cm^3 rubber ring was placed on a porous ceramic pressure plate and filled with the soil sludge. The pressure plate was placed in a pressure pan and incubated at a relative pressure of 14,000 hPa for the Wilting Point estimate, which is more than sufficient pressure for sandy soils like the ones tested (Wiecheteck et al. 2020). The undisturbed soil core was saturated by capillary action and incubated in a pressure pan at 98 hPa for the Field Capacity estimate. After a two-week incubation period, the samples were removed from the plate, weighed, oven-dried at 70ºC, and weighed a second time to determine the difference in gravimetric water content (w). Gravimetric water content was converted to volumetric water content (θ) by: $\theta = w \cdot p_b \,/\, p_w$; where p_b is based on the measured dry mass of the undisturbed soil core sample and the known soil core volume; the density of water (p_w) is assumed to be 1 g ml^{-1}. Plant Available Water (PAW) was estimated by subtracting the Field Capacity measurement (θ_{FC}) from the Wilting Point (θ_{WP}) measurement: $PAW = \theta_{FC} - \theta_{WP}$.

5.2.4 Statistical analyses

We assessed OA impacts on soil hydro-physical properties using repeated-measures generalized linear mixed-effects models (GLMEM) of a gamma distribution family. To account for imbalances in the data while allowing an assessment of the impact of the site, two sets of models were fit; one set was fitted to all data at each site, and the other set was fitted only to the combined data of the mutually shared OA treatments at both sites (i.e. control, compost and manure). The first set of models was designed to include additive and interactive effects between the factors *amendment* and sampling *season* (eq. 5.3). The second set of models, applied to data from the shared treatments, included the additive and interactive effects of the *site* (eq. 5.4). Both sets of models included random error effects for sampling year and treatment block:

$$y_{ijlm} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{l(i)} + \varepsilon_m \qquad (5.3$$

$$z_{ijklm} = \mu + \alpha_i + \beta_j + \delta_k + (\alpha\delta)_{ik} + (\beta\delta)_{jk} + (\alpha\beta)_{ij} + (\alpha\beta\delta)_{ijk} + \varepsilon_{l(i,k)} + \varepsilon_{m(k)} \qquad (5.4$$

Where $y_{ijlm} \in (0, \infty)$ is the measured hydro-physical property at each site for amendment i, season j, block l, and year m; and $z_{ijklm} \in (0, \infty)$ is the measured hydro-physical property for shared treatments at both sites including, in addition to the terms of eq. 3, a site factor k and its interactive effects. Furthermore, μ is the population mean; α_i,, β_j, and δ_k are the fixed effects of amendment, season and site. For the site-specific model $\varepsilon_{l(i)}$ is the random block error effect per treatment, and ε_m is the random year error effect. For the shared treatment model $\varepsilon_{l(i,k)}$ is the random block error effect per treatment and per site, and $\varepsilon_{m(k)}$ is the random year error effect per site.

The models were fit to the acquired data through maximum likelihood estimation by Laplace approximation. The variance associated with each effect factor was evaluated through a multi-way analysis of deviance testing by Type III Wald chi-square tests with power factor α=0.1. Subsequently, for each season, statistical significance of the improvements in soil properties of OA amended soils relative to the unamended control soil was determined through pairwise comparison of OA amended and control soils using single-tailed, Sidak post-hoc tests. Sidak post-hoc tests were then applied a second time to test for the statistical significance of seasonal differences in soil improvements for each OA through multiple pairwise comparisons of the improvement relative to the control of each season, for each OA. The results of these tests are presented in bar graphs together with the estimated marginal means (EMMs) of seasonal improvements and seasonal differences per OA. Presenting the data as EMMs allows representation of OA effects while accounting for imbalances in the data (Lenth 2020).

The water retention data, which were restricted in sample size due to the loss of data after using a leaky pressure plate, were scaled to the observations of the control soil ($WR_{OA,impact} = \frac{WR_{OA} - WR_{Control}}{WR_{Control}}$). The results, which included negative values, were approximated by a Gaussian distribution and fit to a linear mixed-effects model (LMEM).

To evaluate the effect of organic matter application on hydro-physical improvements during each season, as well as the differences between seasons, simple linear regression models (LMs) were built. The LMs relate different forms of expression of OA application rates (i.e. as organic matter, fresh matter or dry matter) as well as OA compositional properties (i.e. total carbon or nitrogen concentrations, organic N, P or K concentrations and C:N, C:P or N:P ratios) to the observed changes in soil hydro-physical properties. We identified the OA property with the strongest influence on each respective soil hydro-physical property by comparing the significance and size of the correlation coefficient for each model. All statistical analyses were performed using the emmeans (Lenth 2020) and lme4 (Bates et al. 2015) packages in an RStudio programming environment (RStudio Team 2020).

5.2.5 Impact classification for temporal response

The temporal impact of OAs on each soil property was classified into one of four groups to simplify comparison:

1. *Transient*, where a significant improvement was observed in an earlier but not a later sampling season;
2. *Persistent*, where significant improvements were observed for both earlier and later sampling seasons, and/or sampling season did not affect the observed improvement;
3. *Lagged*, where a significant improvement was not observed for an earlier sampling season but was observed for a later sampling season; and
4. *Enhanced*, where a significant improvement was observed in an earlier season as well as a later season, and a significant enhancement of this improvement was observed between sampling seasons.

5.3 RESULTS

5.3.1 Main and seasonal interaction effects of organic amendments on soil hydro-physical properties

Most of the evaluated soil hydro-physical properties were significantly affected by the *amendment* applied, except for infiltration capacity at the podzol site (p<0.1). This *amendment* effect depended on the *season* for bulk density and infiltration capacity at the anthrosol site, aggregate stability for the podzol site, and water retention at both sites (p<0.1;Table 5.1). We therefore conditionally accept the hypothesis i) that improvements in soil hydro-physical properties are significantly affected by the OA treatments - except for infiltration capacity at the podzol site - and ii) that these improvements are significantly different depending on sampling season for at least one of the sites. Moreover, we observe that – for the treatments shared between sites– the effects of OAs on bulk density and aggregate stability varied strongly per site.

Table 5.1 Analysis of deviance Chi-Square values for the GLMEMs for various soil hydro-physical properties. Higher Chi-Square values indicate an increased likelihood that the detected variation in the data occurs due to the influence of the effect and not by chance. Site interaction effects are only representative of the shared treatments (i.e. control, compost and manure treatments). Sign. codes: p<0.001 = '***'; p<0.01 = '**'; p<0.05 = '*'; p<0.1 = '•'.

Analysis of Deviance	**Chi Square-value**			
Wald Chi-Square - Type III	**Bulk Density**		**Infiltration Capacity**	
Per Site (Eq. 3)	**Phaeoz.**	**Podzol**	**Phaeoz.**	**Podzol**
Amendment	8.25•	10.9*	28.2***	8.79
Season	0.72	3.96*	0.05	4.51*
Amendment:Season	7.96•	7.70	16.1**	6.04
Shared treatments (Eq. 4)				
Amendment	14.6***		0.21	
Site	5.01*		0.94	
Season	5.86*		7.18**	
Amendment:Site	0.37		1.30	
Amendment:Season	9.95**		1.00	
Site:Season	0.63		1.84	
Amendment:Site:Season	4.41		1.82	

Table continued on next page

Table 5.1 Continued.

	Aggregate Stability		Water Retention	
Per Site (Eq. 3)	**Phaeoz.**	**Podzol**	**Phaeoz.**	**Podzol**
Amendment	20.7***	15.6*	31.3***	23.6***
Season	0.61	0.11	1.00	0.01
Amendment:Season	5.28	16.0*	48.2***	8.51•
Shared treatments (Eq. 4)				
Amendment	2.43		2.99	
Site	5.28*		0.00	
Season	0.13		0.04	
Amendment:Site	0.22		8.87*	
Amendment:Season	2.75		4.64•	
Site:Season	0.01		0.01	
Amendment:Site:Season	1.61		13.3**	

5.3.2 Bulk Density

Sidak post-hoc testing demonstrated that bulk density was significantly reduced for various OAs in the summer at both sites, but not in the winter at the podzol site ($p<0.1$; Figure 1, Appendix S). Greatest decreases in bulk density were observed for compost in the summer at the podzol site, reducing bulk density by 0.12 g cm^{-3} (-9.8%). Reductions in bulk density attained in summer had largely disappeared by winter for compost (Δ0.08 g cm^{-3}) at the anthrosol site and compost (Δ0.13 g cm^{-3}) and Bokashi (Δ0.06 g cm^{-3}) at the podzol site ($p<0.1$; Appendix S). The impact of different OAs on bulk density differed within a single season by 2.5% to 9.8% relative to the unamended control (Appendix T).

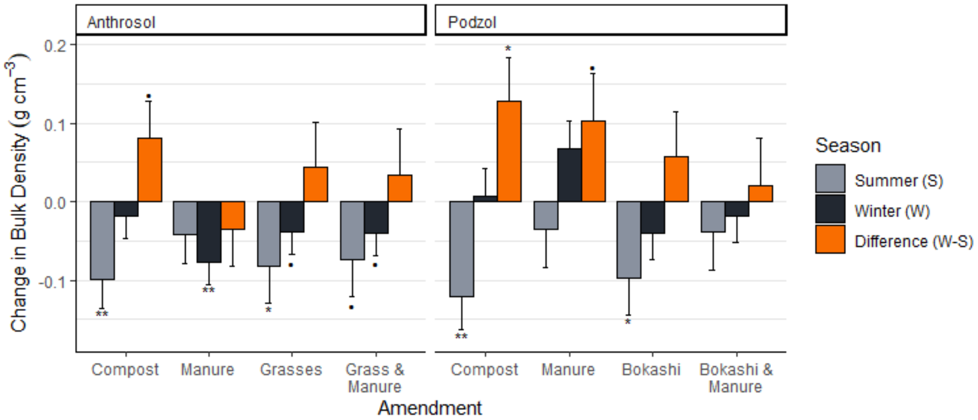


Figure 5.1 EMMs of bulk density after 3 years of repeated OA application. Symbols at grey (summer) and black (winter) bars indicate the level of significance of the change in bulk density when compared to the control, while symbols for orange bars indicate the significance of the difference in decrease relative to the control between winter and summer for that OA treatment: $p<0.01$ = '**'; $p<0.05$ = '*' 0.05; $p<0.1$ = '•'.

5.3.2.1 Effect of amendment application rate

Amendment application rates, expressed as either organic matter, fresh matter or dry matter, were correlated to decreases in bulk density only in summer at the anthrosol site (Figure 5.2). Strongest correlations were observed when amendment application rates were expressed in the form of dry matter (R_{DM}=0.92***; Table 5.2). Differences between seasons for each OA treatment were also only significant at the anthrosol site, where the strongest correlation was again observed for the dry matter application rate (R_{DM}=0.92***; Table 5.2, Figure 5.2).

Table 5.2 Correlation coefficients for linear regression models relating amendment application rates to seasonal improvements and differences in bulk density. Significant correlations are emboldened. $p<0.001$ = '***'; $p<0.01$ = '**'; $p<0.05$ = '*'; $p<0.1$ = '•'

Corr. Coef. OA property vs. Bulk Density	**Anthrosol**			**Podzol**		
	Summer	**Winter**	**Difference**	**Summer**	**Winter**	**Difference**
Organic matter	0.68*	0.11	0.81**	0.3	0.23	0.19
Fresh matter	0.76*	0.3	0.31	0.09	0.04	0.16
Dry matter	**0.92*** **	0.01	**0.92*** **	0.51	0.32	0.33

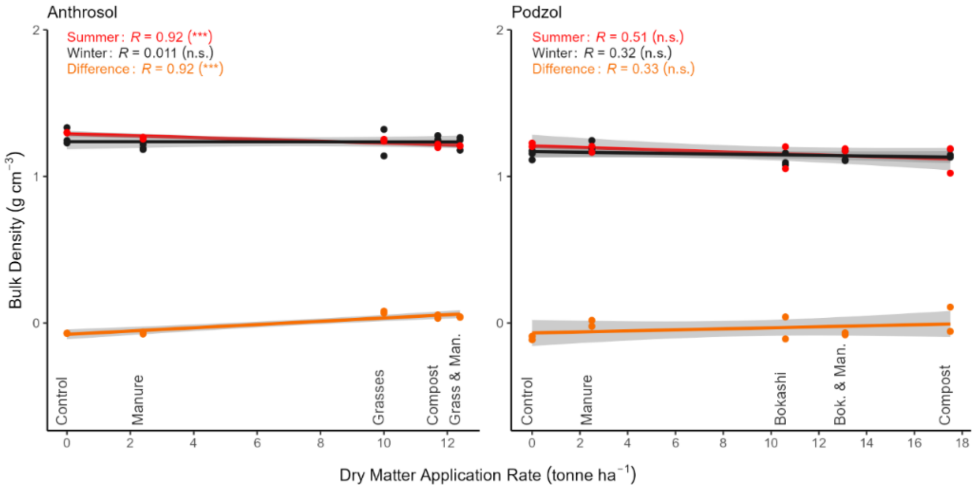


Figure 5.2 Bulk density response to different rates of total dry matter application in the experimental period of 3 years with the different OAs. Symbols indicate the significance of the regression trend: $p<0.001$ = '***'; $p>0.1$ = not significant (n.s.).

5.3.2.2 Effect of amendment composition

Seasonal decreases and inter-seasonal differences in bulk density were correlated to OA compositional properties at both sites, except for summer at the podzol site (Table 5.3). At the anthrosol site, summer reductions in bulk density correlated most strongly to OAs phosphorus concentrations (RP=0.74*), winter reductions to carbon and active nitrogen concentrations (RC,RN-active=0.47•), and differences between seasons to C:N ratio's (RC:N=0.72*). While neither reductions per season, nor differences between seasons, were significantly correlated to OM application rates at the podzol site (Appendix S1, Figure 2), we did observe correlations of winter improvements with OA total carbon (RC=0.59*) and nitrogen concentrations (RNt=0.61*), and a correlation of inter-seasonal differences with potassium concentrations (RK=0.58•).

Table 5.3 Correlation coefficients for linear regression models relating OA composition (concentrations and ratios) to seasonal improvements (reductions) and differences in bulk density. The maximum of each column is presented in bold. Signif. codes: p<0.05 = '*'; p<0.1 = '•'.

Correlation Coefficients	**Anthrosol**			**Podzol**		
OA property vs. Bulk Density	**Summer**	**Winter**	**Difference**	**Summer**	**Winter**	**Diff.**
C_{Total}	0.17	**0.47•**	0.05	0.13	0.59*	0.25
N_{Total}	0.16	0.46•	0.23	0.12	**0.61***	0.28
N_{Active}	0.13	**0.47•**	0.17	0.08	0.38	0.18
$P_{organic}$	**0.74***	0.24	0.3	0.54	0.2	0.46
$K_{Organic}$	0.64*	0.03	0.37	0.45	0.21	**0.58•**
C:N	0.54	0.27	**0.72***	0.31	0.04	0.34
C:P	0.35	0.21	0.67*	0.13	0.2	0.3
N:P	0.55	0.31	0.64*	0.2	0.28	0.41

5.3.3 Infiltration Capacity

Infiltration capacity was significantly increased in summer but not in winter for multiple OAs at the anthrosol site; and both in summer and winter for several OAs at the podzol site (p<0.1;Figure 5.3, Appendix S). Greatest increases were observed in summer, where the grass & manure treatment increased infiltration capacity at the anthrosol site by 7.2 mm min^{-1} (108%) and WWR at the podzol site by 5.52 mm min^{-1} (99%). Summer improvements at both sites had significantly diminished by winter for all relevant treatments at the Anthrosol site but only for WWR at the podzol site (Δ-4.82 mm min^{-1}; p<0.1; Appendix S). The impact of different OAs on infiltration capacity differed within a single season by 26.4% to 100.8% relative to the unamended control (Appendix T).

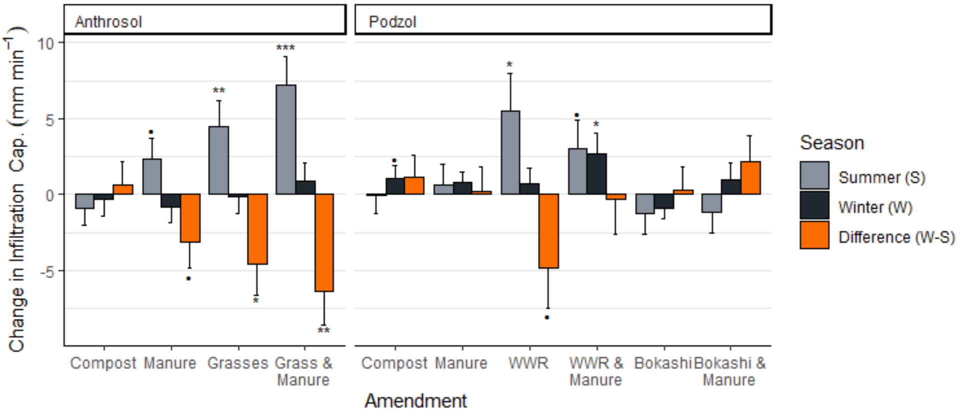


Figure 5.3 EMMs of infiltration capacity response to repeated OA application. Symbols at grey (summer) and black (winter) bars indicate the level of significance of the increase when compared to the control for each season, while symbols at orange bars indicate the significance of the difference between winter and summer for that OA treatment: p<0.001 = '***'; p<0.01 = '**'; p<0.05 = '*' 0.05; p<0.1 = '•'.

5.3.3.1 Effect of amendment application rate

Amendment application rates in the form of organic matter (OM) correlated with increases in infiltration capacity in summer (R_{OM}=0.59**) and winter (R_{OM}=0.42*) at the anthrosol site, whereas, for the podzol site, only a weak correlation for winter increases was observed with fresh matter application rate (R_{FM}=0.32•;Table 5.4). Also, the differences between seasons for each OA treatment correlated only to OM application rates and only at the anthrosol site (R_{OM}=0.47*•;Table 5.4, Figure 5.4).

Table 5.4 Correlation coefficients for linear regression models relating amendment application rates to seasonal improvements and differences in infiltration capacity. Significant correlations are emboldened. Signif. codes: p<0.001 = '***'; p<0.01 = '**'; p<0.05 = '*'; p<0.1 = '•'.

Correlation Coefficients	**Anthrosol**			**Podzol**		
OA property vs. Infiltration Capacity	**Summer**	**Winter**	**Diff.**	**Summer**	**Winter**	**Diff.**
Organic matter	**0.59****	**0.42***	**0.47***	0.08	0.25	0.06
Fresh matter	0.31	0.06	0.31	0.05	**0.32•**	0.16
Dry matter	0.26	0.28	0.28	0.23	0.11	0.21

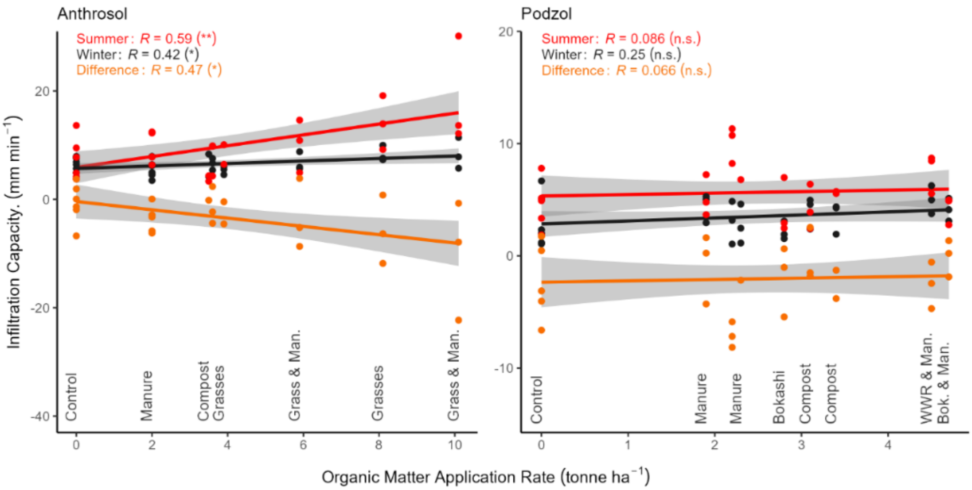


Figure 5.4 Infiltration capacity response to different rates of organic matter application. Symbols indicate significance of the regression trend: $p<0.01$ = '**'; $p<0.05$ = '*' 0.05; $p<0.1$ = '•'; $p>0.1$ = not significant (n.s.).

5.3.3.2 Effect of organic amendment composition

Seasonal increases and inter-seasonal differences demonstrated *weaker* correlations to amendment composition than OM application rates at both sites (Table 5.5). At the anthrosol site, summer improvements were significant but less strongly related to C:P ratios than to organic matter application rates ($R_{C:P}$=0.52** vs. R_{OM}=0.59**), while no compositional property was related to winter improvements. Differences between seasons at the anthrosol site also were slightly less correlated with C:P and N:P ratios than with OM application rates ($R_{C:P}$, $R_{N:P}$ =0.41* vs. R_{OM}=0.47*). At the podzol, OA composition properties showed no correlation to seasonal improvements nor inter-seasonal differences.

Table 5.5 Correlation coefficients for linear regression models relating OA composition (as concentrations and ratios) to seasonal improvements and differences in infiltration capacity. The maximum of each column is presented in bold. Signif. codes: $p<0.01$ = '**'; $p<0.05$ = '*'; $p<0.1$ = '•'.

Corr.Coef.	**Anthrosol**			**Podzol**		
OA property vs. Infil. Cap.	**Summer**	**Winter**	**Difference**	**Summer**	**Winter**	**Difference**
C_{Total}	0.28	0.1	0.27	0.23	0.09	0.05
N_{Total}	0.15	0.2	0.17	0.24	0.08	0.05
N_{Active}	0.22	0.16	0.23	0.22	0.09	0.06
$P_{organic}$	0.14	0.13	0.04	0.09	0.15	0.02
$K_{Organic}$	0.28	0.09	0.12	0.09	0.12	0.02
C:N	0.42*	0.17	0.37•	0.17	0.17	0.08
C:P	**0.52****	0.3	**0.41***	0.18	0.14	0.11
N:P	0.50**	0.19	**0.41***	0.16	0.14	0.12

5.3.4 Aggregate stability

Aggregate stability was significantly increased for various OAs in both summer and winter at both sites ($p<0.1$; Appendix S, Figure 5.5). Greatest increases were observed in the winter, where the grass & manure treatment improved aggregate stability at the anthrosol site by 0.75 mm (60.0%) and bokashi at the podzol site by 0.73 mm (40.5%). Aggregate stability was significantly improved between summer and winter by compost (Δ0.19 mm) and manure (Δ0.35 mm) at the anthrosol site and by bokashi (Δ1.21 mm) at the podzol site ($p<1$; Appendix S, Figure 5.5). The impact of OAs on aggregate stability differed within a single season by 8.2% to 46.3% relative to the unamended control (Appendix T).

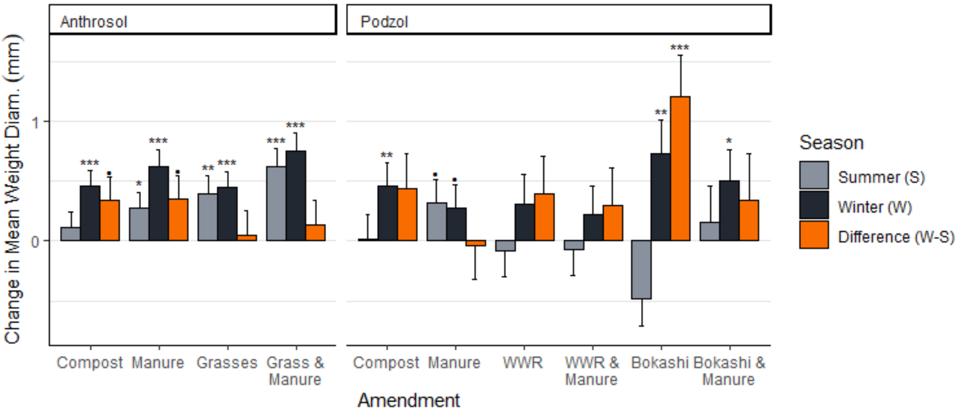


Figure 5.5 EMMs of aggregate stability response to repeated OA application. Symbols at grey (summer) and black (winter) bars indicate the level of significance of the increase when compared to the control for each season, while symbols at orange bars indicate the significance of the difference between winter and summer for that OA treatment: $p<0.001$ = '***'; $p<0.01$ = '**'; $p<0.05$ = '*' 0.05; $p<0.1$ = '•'.

5.3.4.1 Effect of amendment application rate

Amendment application rates as fresh matter correlated strongly to increases in aggregate stability in summer ($R_{FM}=0.61$***) and winter ($R_{FM}=0.42$*) at the anthrosol site, whereas application rates expressed as dry matter correlated most strongly to winter increases at the podzol site ($R_{DM}=0.53$**;Table 5.6). The seasonal differences at the anthrosol site were not related to the OA application rate, whereas at the podzol site, they correlated again to the dry matter application rate ($R_{DM}=0.48$*;Table 5.6, Figure 5.6).

Table 5.6 Correlation coefficients for linear regression models relating amendment application rates to seasonal improvements and differences in aggregate stability. Significant correlations are emboldened. Signif. codes: p<0.001 = '***'; p<0.01 = '**'; p<0.05 = '*'; p<0.1 = '•'.

Correlation Coefficients OA property vs. Aggregate Stability	**Anthrosol**			**Podzol**		
	Summer	**Winter**	**Difference**	**Summer**	**Winter**	**Difference**
Organic matter	0.61***	0.42*	0.05	0.02	0.33•	0.25
Fresh matter	**0.69*****	**0.57****	0.14	0.19	0.26	0.02
Dry matter	0.37•	0.39*	0.2	0.13	**0.53****	**0.48***

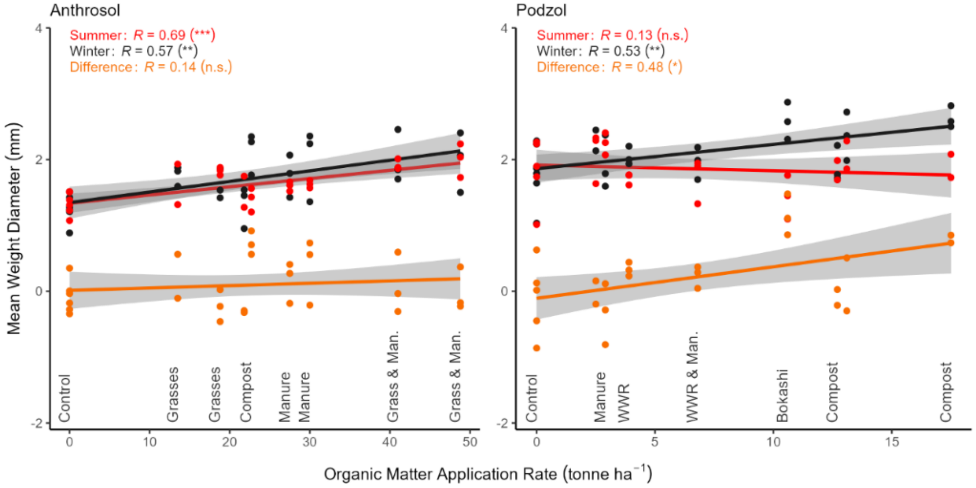


Figure 5.6 Aggregate stability response to different amendment application rates expressed in the form of fresh matter for the anthrosol site and dry matter for the podzol site because of their respective greatest significance. Symbols indicate significance of the regression trend: p<0.001 = '***'; p<0.01 = '**'; p<0.05 = '*' 0.05; p>0.1 = not significant (n.s.).

5.3.4.2 Effect of amendment composition

Seasonal increases and inter-seasonal differences in aggregate stability demonstrated a *weaker* correlation to OA compositional properties than to OM application rates at both sites (Table 5.7 and Table 5.6). At the anthrosol site, summer increases were most strongly correlated to N:P ratios ($R_{N:P}$=0.61*** vs. R_{FM}=0.69***), and winter increases were most strongly correlated to C:N and N:P ratios ($R_{C:N}$,$R_{N:P}$=0.46* vs. R_{FM}=0.57**). Seasonal differences correlated only with phosphorus (R_P=0.42*) and potassium concentrations (R_K=0.39*). At the podzol site, OA application rates did not correlate to summer increases, whereas a weak correlation was observed with total nitrogen concentrations ($R_{N\text{-}Total}$=0.37•). Weaker correlations with OA composition than OA application rates were observed for winter increases, which correlated with C:N ratios ($R_{C:N}$=0.38* vs. R_{DM}=0.53**), and the difference between seasons, which correlated with phosphorus concentrations (R_P=0.39• vs. R_{DM}=0.48**).

Table 5.7 Correlation coefficients for linear regression models relating OA composition (as concentrations and ratios) to seasonal increases and differences in aggregate stability. The maximum of each column is presented in bold. Signif. codes: p<0.001 = '***'; p<0.01 = '**'; p<0.05 = '*'; p<0.1 = '•'.

Correlation Coefficients OA property vs. Aggr. Stab.	**Anthrosol**			**Podzol**		
	Summer	**Winter**	**Difference**	**Summer**	**Winter**	**Difference**
C_{Total}	0.41*	0.44*	0.2	0.34•	0.03	0.26
N_{Total}	0.32	0.41*	0.22	**0.37•**	0.04	0.29
N_{Active}	0.46*	0.44*	0.16	0.24	0.09	0.08
$P_{organic}$	0.12	0.45*	**0.42***	0.16	0.34•	**0.39•**
$K_{Organic}$	0.14	0.24	0.39*	0.07	0.08	0.00
C:N	0.60***	**0.46***	0.12	0.04	**0.38***	0.35•
C:P	0.53**	0.35•	0.06	0.16	0.3	0.13
N:P	**0.61*****	**0.46****	0.12	0.24	0.32•	0.07

5.3.5 Water Retention

Water retention was significantly increased at the anthrosol site in both seasons for the grass & manure treatments and in winter additionally for the grasses treatments. At the podzol site, it was significantly improved in summer for WWR & manure and bokashi & manure, and in winter for bokashi and bokashi & manure (p<0.1; Figure 7, Appendix S). Greatest increases were observed in the winter, where water retention was improved for the grasses treatment at the anthrosol site by 57% and for the bokashi & manure treatment at the podzol site by 77%. Water retention at both sites had significantly improved between summer and winter only for the grasses treatment (Δ25%) at the anthrosol site (p<1; Appendix S). The impact of OAs on water retention differed within a single season by 11.1% to 77.8% relative to the unamended control (Appendix T).

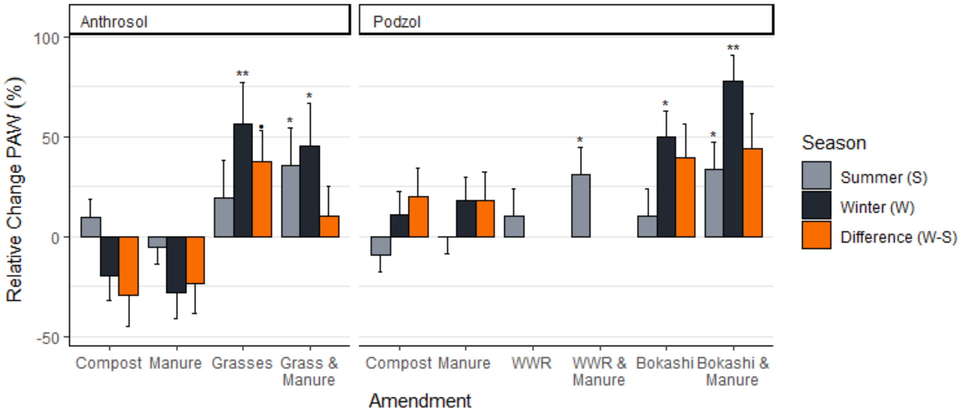


Figure 5.7 EMMs of water retention response to repeated OA application. Symbols above grey (summer) and black (winter) bars indicate the level of significance of the improvement when compared to the control for each season, while symbols above orange bars indicate the significance of the difference between summer and winter for that OA treatment: $p<0.01$ = '**'; $p<0.05$ = '*' 0.05; $p<0.1$ = '•'.

5.3.5.1 Effect of amendment application rate

Amendment application rates correlated to increases in water retention in both seasons at both sites when expressed as organic matter (Table 5.8). At the anthrosol site, these correlations were relatively stronger (summer: R_{OM}=0.94***; winter R_{OM}=0.82•) than at the podzol site (summer: R_{OM}=0.55•; winter R_{OM}=0.83•; Appendix T4). The differences between seasons, however, were linearly related to OM application rates only at the podzol site (R_{OM}=0.95*; Table 5.8, Figure 5.8). Due to the loss of one year of winter data, the standard error of winter and season difference trends are much higher than for other soil properties.

Table 5.8 Correlation coefficients for linear regression models relating amendment application rates to seasonal improvements and differences in water retention. Significant correlations are emboldened. Signif. codes: $p<0.001$ = '***'; $p<0.01$ = '**'; $p<0.05$ = '*'; $p<0.1$ = '•'.

Correlation Coefficients	**Anthrosol**			**Podzol**		
OA property vs. Water Retention	**Summer**	**Winter**	**Difference**	**Summer**	**Winter**	**Difference**
Organic matter	**0.94*** **	**0.82•**	0.54	0.55•	**0.83•**	**0.95***
Fresh matter	0.5	0.13	0.23	0.58•	0.76	0.77
Dry matter	0.71*	0.5	0.14	0.01	0.45	0.79

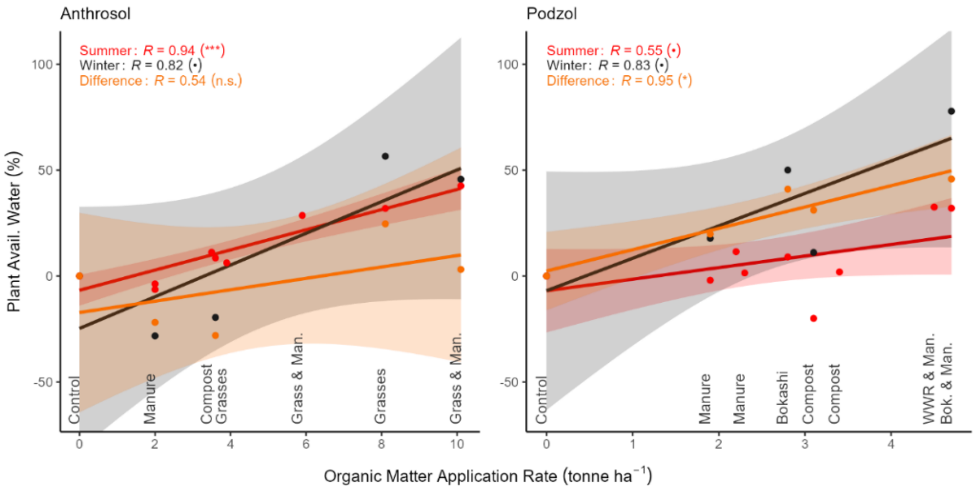


Figure 5.8 Water retention response to different rates of organic matter application. Symbols indicate significance of the regression trend: $p<0.001$ = '***'; $p<0.05$ = '*' 0.05; $p<0.1$ = '•'; $p>0.1$ = not significant (n.s.).

5.3.5.2 *Effect of amendment composition*

For water retention, the seasonal improvements and inter-seasonal differences demonstrated a *weaker* correlation to OA compositional properties than to OM application rates at both sites (Table 5.9 and Table 5.8). At the anthrosol site, only summer increases were significantly correlated with OA compositional properties, namely C:N and C:P ($R_{C:N}=0.58$•, $R_{C:P}=0.63$• vs. $R_{OM}=0.94$***). At the podzol site, only the differences between seasons were significantly correlated to OA compositional properties ($R_P=0.89$*, $R_{C:N}=0.87$• vs. $R_{OM}=0.95$*).

Table 5.9 Correlation coefficients for linear regression models relating OA composition (as concentrations and ratios) to seasonal improvements and differences in water retention. The maximum of each column is presented in bold. Signif. Codes: $p<0.05$ = '*'; $p<0.1$ = '•'.

Cor. Coef. OA property vs. Water Retention	**Anthrosol**			**Podzol**		
	Summer	**Winter**	**Difference**	**Summer**	**Winter**	**Difference**
C_{Total}	0.00	0.02	0.07	0.21	0.04	0.03
N_{Total}	0.17	0.3	0.35	0.16	0.01	0.01
N_{Active}	0.04	0.11	0.16	0.43	0.42	0.36
$P_{organic}$	0.08	0.38	0.66	0.11	0.52	**0.89***
$K_{Organic}$	0.01	0.44	0.67	0.21	0.05	0.41
C:N	0.58•	0.6	0.43	0.39	0.7	0.87•
C:P	**0.63•**	0.76	0.67	0.4	0.6	0.67
N:P	0.54	0.57	0.38	0.27	0.48	0.64

5.3.6 Seasonal variability of organic amendment impacts

OAs varied strongly in their seasonal impacts on soil properties relative to the control (Table 5.10). Greatest seasonal impacts were observed for the WWR treatment (on average 47% relative to the control). Least impact was observed for manure at the podzol site (11.7%). Infiltration capacity had the greatest seasonal variation in OA impacts, showing an average 47% difference between summer and winter OA impacts relative to the control. Least variation was observed in bulk density, showing average seasonal differences of 5%.

Table 5.10 Seasonal differences in OA impacts as percent relative to control (%Winter - %Summer) for different OA treatments. Original data presented in Appendix S. Symbols indicate the significance of the difference between winter and summer impacts for each OA treatment: p<0.01 = '**'; p<0.05 = '*' 0.05; p<0.1 = '•', where '†' indicates that an OA impact was significant for one season but not another while the difference between seasons was not statistically significant. *n.d.* is no data.

Seasonal Difference OA Impact Rel. Control	Site	Bulk Density	Infiltr. Capacity	Aggreg. Stability	Water Retention	Averg Abs. Diff.
			[%W-%S]			
Compost	**Anthr.**	6.1•	9.7	27.8•	-29.4	18.3
	Podzol	10.7*	41.6†	24.5†	20.2	24.3
Manure (M)	**Anthr.**	-3.2•	-45.5•	28.7•	-23.2	25.2
	Podzol	8.6	18.4	-1.6	18.1	11.7
Grasses (G)	**Anthr.**	3.0	-68.9*	6.2	10.1•	22.1
G&M	**Anthr.**	2.2	-96.2**	13.7	25.6	34.4
WWR	**Podzol**	*n.d.*	-73.0•	21.5	*n.d.*	47.3
WWR&M	**Podzol**	*n.d.*	46.9	16.0	*n.d.*	31.5
Bokashi (B)	**Podzol**	4.7	-12.4	66.4***	39.5†	30.8
B&M	**Podzol**	1.5	58.5	19.2†	44.3	30.9
Average Abs. Difference		5.0	47.1	22.6	26.3	27.6
Standard Deviation σ		2.9	25.5	16.0	9.9	8.8

The classification of the temporal variability in OAs impacts shows how some OAs have a lagged effect on one property and a persistent, transient or enhanced effect on another, and how one soil property can demonstrate a transient response to one type of OA, but a lagged response to another type of OA (Table 5.11). It furthermore illustrates differences between sites. In general, bulk density appeared to be transiently improved at the podzol site regardless of the OA treatment, and transiently or persistently improved at the anthrosol site depending on the OA treatment. Infiltration capacity was mostly only transiently improved, especially at the anthrosol site, while for water retention the improvements were either lagged or persistent depending again on the OA treatment. For aggregate stability, most OAs had a persistent, lagged or enhanced effect. Furthermore, the classification shows that no specific OA treatment consistently outperforms the others across all soil hydro-physical properties and sites. The limited significance of some of the OA treatments at the podzol site (with footnotes in Table 5.11) might be explained by their lower data count (one year instead of two years of sampling).

Table 5.11 Classification of amendment effects per soil property and site.'-' indicates no effect, and *n.d.* is no data.

	Amendment Impact Classification			
	Bulk Density	**Infiltration Capacity**	**Aggregate Stability**	**Water Retention**
Anthrosol				
Compost	Transient	-	Lagged	-
Manure	Lagged	Transient	Enhanced	-
Grasses	Persistent	Transient	Persistent	Lagged
Grasses&Manure	Persistent	Transient	Persistent	-
Amendment app.	Lagged	Transient	Persistent	Persistent
Podzol				
Compost	Transient	Lagged	Lagged	-
Manure	Transient	-	Persistent	-
WWR[a]	*n.d.*	Transient	-	*n.d.*
WWR&Manure[a]	*n.d.*	Persistent	-	*n.d.*
Bokashi[b]	Transient	-	Lagged	Lagged
Bokashi&Manure[b]	-	-	Lagged	Persistent
Amendment app.	-	-	Lagged	Enhanced

a. Sampled only in year two of the experiment
b. Sampled only in year three of the experiment

5.4 DISCUSSION

5.4.1 Improvements following amendment application

Results showed substantial improvements in bulk density (up to -9.8% decrease), infiltration capacity (up to 108.1% increase), aggregate stability (up to 60.0% increase) and water retention (up to 77.8% increase) for most of the investigated OAs within three years of repeated application (Appendix T). While OA application is often regarded as a long-term strategy for soil improvement, as soil properties are typically slow to evolve in response to OA treatments (Diacono and Montemurro 2011), the current experiment corroborates findings that significant soil improvements can already be achieved within a few years (Carron et al. 2015; Castellini et al. 2022; Delibacak et al. 2009; Ouyang et al. 2013).

OA application generally improved soil hydro-physical properties, but the magnitude of these improvements differed significantly depending on the OA treatment. Differences between OA impacts (relative to the control) were as large as 9.6% for bulk density, 135% for infiltration capacity, 43% for aggregate stability, and 85% for water retention, depending on the season (Appendix T). Up to 140% differences for infiltration capacity have also been observed in other studies (Zamani et al. 2016). This suggests that not all OAs are equally effective in contributing to building soil resilience, as their impacts may not have developed yet or already have dissipated by the time that season-specific challenges occur.

Temporal effects of OAs were significant for all soil hydro-physical properties and were frequently larger than spatial, site-dependent differences (Table 5.1). Similar greater effects of temporal than (field-scale) spatial variability on soil hydro-physical properties have also been observed for unamended soils (van Es et al. 1999). Temporal influences such as climate and OAs thus appear to exert greater control on soil changes than differences that arise due to field-scale heterogeneity or differences between sites. Highest temporal variability was observed for the combined grasses and manure treatment, which showed nearly a 100% difference between summer and winter seasons for infiltration capacity. On average, OA treatments varied in their seasonal impacts relative to the control by 5% for bulk density, 47.1% for infiltration capacity, 22.6% for aggregate stability and 26.3% for water retention. Field studies on *unamended* soils have also noted short-term temporal variation in soil hydro-physical properties such as bulk density, porosity, aggregate stability and hydraulic conductivity – of which the latter furthermore demonstrated large differences in its temporal patterns for different soils (Jirků et al. 2013; Scott et al. 1994). To explain this variation, Popolizio et al. (2022) identified soil moisture as a critical factor. Different soil moisture concentrations are believed to significantly influence changes in bulk density and hydraulic conductivity through effects such as swelling and slaking. Such differences could explain contrasting variations between the anthrosol and podzol sites but cannot explain differences in seasonal variability of OA impacts within each site, as seasonal water balances are the same for all treatments at a site. It would be interesting for future studies to measure seasonal changes in biological properties known to affect soil structure (Kinsbursky, Levanon, and Yaron 1989; Oades 1984, 1993), and evaluate whether and how these relate to short-term changes in hydro-physical soil properties.

5.4.2 Influence of quantity versus quality

Diversity in the composition and application rates of OAs allowed assessing the relative importance of OA quantity versus soil hydro-physical properties. Unfortunately, no single OA quantity or quality indicator could consistently explain the observed temporal trends for any soil property at either site. However, seasonal improvements and differences between seasons generally correlate better with OA quantity indicators (i.e. application rates) than with OA quality indicators (i.e. compositional properties). Other OA studies without combined mineral fertilizer applications have similarly observed the importance of OA application quantity over differences in OA type (Barzegar, Yousefi, and Daryashenas 2002; Castellini et al. 2022; Delibacak et al. 2009; Tejada and Gonzalez 2008).

Of the OA quality indicators, the C:N and N:P ratios, as well as P concentrations, generally demonstrated more and/or stronger correlations to both seasonal improvements and differences between seasons. The recurrence of nitrogen and phosphorus as a quality indicator is not surprising as the stoichiometric balance of these with other elements is recognized to be an important regulator of organic matter decomposition (Manzoni et al. 2010; Mooshammer et al. 2017). Since no single OA quality indicator performed best at both sites for any soil hydro-physical property, the impact of OA composition likely also depends on the conditions of the local soil environment. A complex interaction effect with the soil biotic and abiotic properties prior to OA application can often explain subsequent changes in the soil (Chen et al. 2022; Hamer and Marschner 2005a; D.-J. D. Kok et al. 2022; Lloyd et al. 2016). Potentially, OA quality may have a more consistent impact on soil improvements in agricultural settings where the total nutrient inputs are not supplemented with mineral fertilizers and are, instead, completely dependent on the nutrients provided by the OAs applied.

While OA quantity correlated better than OA quality to observed changes in soil hydro-physical properties, the strength of these correlations varied significantly depending on the expression of application quantity in either the form of fresh, dry or organic matter. Manure, for instance, due to its high water content, was applied at rates of around 30 kg *fresh matter* ha^{-1} but only 2.5 kg ha^{-1} in terms of *dry matter*. Compost, instead, was applied at much lower rates of 20 kg ha^{-1} *fresh matter* and higher rates of 13 kg ha^{-1} *dry matter*. Also, *organic matter* application rates varied significantly (i.e. ~3 kg ha^{-1} for compost and manure, 4-14 kg ha^{-1} for grasses, etc.; Appendix Q). Differences in the strength of correlation between these metrics suggest that factors such as the initial water content of OAs (fresh versus dry matter) or the ratio of organic to non-organic components (organic matter versus dry or fresh matter) are potentially relevant in explaining differences in OA impacts.

Aggregate stability, for instance, showed stronger correlations than organic matter to application rates in terms of fresh matter, particularly at the anthrosol site (Table 5.6). Such site-dependent effects of manure applications have been observed before (Paré et al. 1999; Roldán, Albaladejo, and Thornes 1996; Whalen and Chang 2002) and have been linked to differences in the leaching rates of aggregate dispersal agents (Guo et al. 2019). Such differences in leaching may also explain our results for the anthrosol site, given its coarser texture and higher infiltration capacity. Alternatively, the strong correlation of aggregate stability with high fresh matter application rates may relate to the slurry-like state of manure, allowing it to infiltrate soil pores and encapsulate soil particles resulting in its more efficient colonization and subsequent stimulation of aggregate stabilization. In general, however, for all soil properties, *organic matter* application rates demonstrated the most consistent correlations to observed improvements at both sites (Figure 5.2, 5.4, 5.6 and 5.8). This underscores the well-established importance of external carbon input as a stimulant of soil biological processes driving changes in the soil (Bronick and Lal 2005; Tang, Yang, and Antonietti 2022; Ward, Capone, and Zehr 2007).

5.4.3 Influence of land management practices

Seasonal variability in OA impacts on hydro-physical properties is likely also influenced by land management practices, as these often involve considerable disturbance of a soil at different spatial and temporal scales (Hu et al. 2018). The occurrence of a disturbance event can affect improvements achieved by OAs, which might be reverted, remain unaffected, or potentially be amplified depending on the soil property and disturbance intensity. At the anthrosol site, for example, OAs with significant impacts all demonstrated a transient improvement in infiltration capacity, where improvements during the summer had completely dissipated by winter. A possible explanation for this consistent response for all OAs may be found in the effect of tillage between seasons at this site. Infiltration capacity measurements are sensitive to the presence of preferential flow paths; thus, OAs potentially improved soil infiltration capacity by stimulating preferential flow path development (Ali et al. 2018). Such soil macro-structures, however, are also sensitive to physical disturbance events (Andreini and Steenhuis 1990; Shipitalo, Dick, and Edwards 2000), and so it is likely that the post-harvest tillage at the anthrosol site destroyed many of the developed preferential flow paths, resulting in the reversal of infiltration capacity improvements by winter. This explanation is furthermore supported by data from the podzol site, which was not tilled post-harvest, and where soils retained some of their improvements providing lagged or persistent effects by winter. Studies on unamended soils has similarly observed greater improvements in soil hydraulic properties when fields were not tilled by conventional means (Arshad, Franzluebbers, and Azooz 1999; Pagliai, Vignozzi, and Pellegrini 2004; Pires et al. 2017). Additional tillage at the podzol site thus potentially contributed to generally reduced OA impacts on bulk density, infiltration capacity and aggregate stability, as well as the greater seasonal differences observed for properties at this site.

Parallel to the challenge of uncovering universal relationships between OA properties with chemical and biological changes in soils (Kögel-Knabner 2017), it also appears that linking OA properties to changes in soil hydro-physical properties is similarly not straightforward given the many possible interaction effects with land management. Moreover, some of the contradicting findings published in studies regarding variation in aggregate stability (Abiven et al. 2009; Albiach et al. 2001) and water retention (Minasny and McBratney 2018) may be partially explained by the combination of temporal variability in these soil hydro-physical properties and differences in study sampling times (Carron et al. 2015).

5.4.4 Design of organic amendment application strategies

Though impacts varied, the application of OAs led to improvements in soil hydro-physical properties for nearly every OA type, at nearly every sampling moment, at both anthrosol and podzol sites. The application of either compost, manure, grasses, grasses&manure, waterway weeds and reeds, waterway weeds and reeds&manure, bokashi, and bokashi&manure, to dynamic agricultural soils thus appears substantially more likely to improve soil water management and crop growth rather than harm them (Abiven et al. 2009; Lal 2020). However, not all investigated OAs appear equally effective for the purpose of improving soil resilience to specific seasonal weather extremes, given the differences in their temporal variability of impacts and the potential interaction of these effects with soil type and management practices. We have demonstrated that these temporal effects were significant for all soil hydro-physical properties, and that they frequently explained similar or greater variation in the data than spatial, site-dependent differences (Table 5.2). This implies that designs of OA application strategies should account for temporal variability in their impacts and not rely on single or annual measurements, as is the current practice (e.g. (Cercioglu 2017; Ferreras et al. 2006; Z. Li et al. 2018; Singh Brar et al. 2015; Tejada and Gonzalez 2008; Yüksel and Kavdır 2020; Zhao et al. 2009). Our findings furthermore underscore that the parameterization of soil hydro-physical properties based solely on soil type may not be appropriate for agricultural lands given their significantly high short-term temporal variability due to soil-management factors such as OA treatments or tillage practices (van Es et al. 1999). Finally, for cultivation soils with fertilizer restriction and soils where OAs are supplemented with synthetic fertilizers, the design of OA application strategies would benefit from increasing the quantity of OA applied rather than the quality, as organic matter application rates demonstrated more consistent and stronger correlations to changes in soil hydro-physical properties than OA compositional properties did.

Most of the OAs investigated in this study are waste products derived from landscape maintenance, i.e. clearing of waterways and mowing of road-verges, in treated or untreated forms. With little to no apparent negative consequence, for at least soil hydro-physical properties, the application of these organic wastes to immediately surrounding agricultural soils may be an efficient means of waste disposal (Sharma et al. 2019). Naturally, soil chemical impacts as well as toxicological, pathological and biological hazards, would require further investigation before the widespread adoption of the less familiar OAs, e.g. waterway residues, in soil improvement practices (Ros, Termorshuizen, and van Dijk 2012).

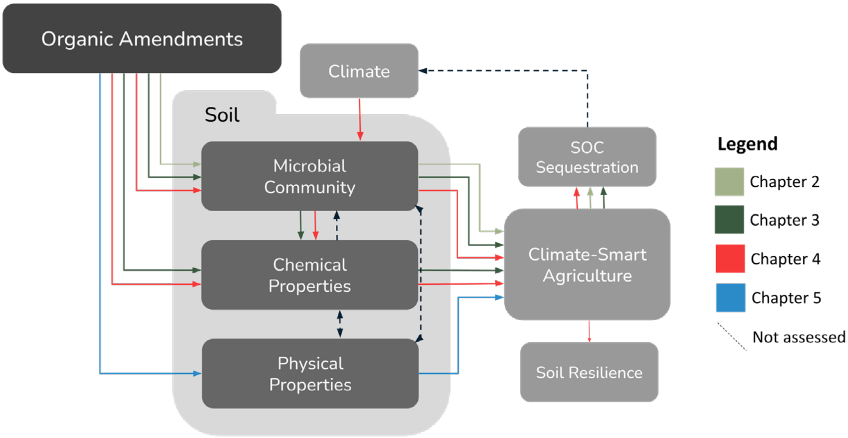
Of the OAs investigated, compost generally produced temporally favourable impacts on hydro-physical properties. Comparing compost impacts is difficult as more than 600 studies on its role in agriculture have been published over the past 11 years alone (Rivier et al. 2022), although the findings of the current study correspond well with the ranges observed elsewhere (Appendix U).

Manure only produced temporally beneficial effects on aggregate stability at the anthrosol site and on bulk density and aggregate stability at the podzol site. Comparatively, the grass & manure combination treatment, which was only applied to the anthrosol soil, seems a more promising alternative to applying manure alone as it produced temporally favourable effects for more soil properties, namely aggregate stability, bulk density, and water retention. The application of manure is a traditional soil improvement strategy that dates back to 6000 B.C. (Bogaard et al. 2013), and consequentially its effects have been extensively studied and reported (Rayne and Aula 2020). Our observed manure impacts are at the lower end of observations in other studies for bulk density (2.1-14%; Celik et al. 2010) and hydraulic conductivity (up to 234%; Fares et al. 2008). Changes in aggregate stability are in a similar range as reported elsewhere (from no significant effects (Karami et al. 2012) to 75% (Celik et al. 2010)).

While OAs like compost and manure have been extensively studied, few experiments have evaluated the potential soil benefits resulting from the application of grasses recovered from public green areas and waterway residues recovered from public waterways and/or their combination with manure. An estimated 770,000 tonnes of dry matter is produced each year in the regular landscape maintenance of public green areas in the Netherlands, indicating an enormous potential for their application as a soil improver (Elbersen and Spijker 2014). Although only tested at one of the sites, our results showed that, when compared to compost, grasses resulted in a similar improvement in bulk density but greater improvements in infiltration capacity, aggregate stability, and water retention, though again the large improvement in the latter was not statistically significant. The impact of waterway residues (WWR) was difficult to assess due to the limited data (only sampled in one year, after two years of application) but appears to outperform compost only in improvements in infiltration capacity. Despite the excellent performance of grasses, their application to the soil posed practical issues. The grasses were difficult to integrate as they stuck to the tillage and harrow blades. For the purpose of the experiment, therefore, we manually facilitated soil integration. An alternative solution that is more easily implementable at an agro-industrial level could be to shred the grasses before application – although this may change the soil response. Nevertheless, grasses recovered from public green areas demonstrated a significant and favorable impact on a soil's hydro-physical properties which warrants further investigation of their utilization potential in agricultural settings.

5.5 CONCLUSION

Our findings show that the application of OAs can improve soil hydro-physical properties up to 108%, but that differences in these improvements between seasons could vary up to 96% depending on the OA and soil property. While no OA property could consistently explain this temporal variability, results demonstrate a greater influence of OA application quantity and a lesser influence of OA composition (i.e. its quality), when OA nutrient differences are offset with mineral fertilizers. Of the OAs investigated, compost generally produced a temporally most favorable impact on the soil hydro-properties, though the improvements in some seasons were sometimes greater for the landscape residues (i.e. grasses, waterway residues, and bokashi fermented waterway residues) and/or their combined application with manure. Overall, findings indicate that not all OAs are equally effective for combating season-specific climatic challenges, given that short-term OA effects may not have developed yet or already have dissipated by the time that an anticipated weather extreme occurs. We, therefore, stress the need to consider the temporal variability of OA impacts when comparing the performance of OAs in existing and future field studies and when designing OA application strategies aimed at improving soil resilience to specific climatic challenges.


Organic Amendments
Climate
Soil
Microbial Community
Chemical Properties
Physical Properties
SOC Sequestration
Climate-Smart Agriculture
Soil Resilience
Legend
Chapter 2
Chapter 3
Chapter 4
Chapter 5
Not assessed