Journal of Environmental Management 369 (2024) 122316

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Optimizing native vegetation establishment in urban soils: Assessing the impacts of organic amendments on specific growth parameters

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ARTICLE INFO

Keywords:
Organic amendments
Composts
Biochar
Vegetation growth
Soluble salts
Leaf area index

ABSTRACT

Following soil disturbances, establishing healthy roadside vegetation can reduce surface water runoff, improve soil quality, decrease erosion, and enhance landscape aesthetics. This study explores the use of organic amendments (OAs) as alternatives to conventional vegetation growth approaches, aiming to provide optimal compost mixing ratios for poor soils, and clarify guidelines for OAs' use in roadside projects. Three sandy loam soils and one loam soil were chosen for the study. Organic amendments included yard waste (Y), food waste (F), turkey litter and green waste-based (T) composts, and wood-derived biochar (B). Treatment applications targeted specific increases in the organic matter (OM) percentage of the soils. A selection of seven native species (grasses and forbs) in a total of 156 pots (4 control soils + 4 soils x 4 OAs x 3 application rates, all prepared in triplicates) was used for the pot study experiment. A significant correlation between electrical conductivity (soluble salts) in soil-OA blends and corresponding percent green coverage (%GC) was found. High salts from the T compost either delayed or curtailed growth. Notably, 3 out of the 4 soils amended with biochar exhibited rapid vegetation coverage during initial growth stages compared to other soil-OA blends but reduced the nitrogen (N) uptake and leaf area in black-eyed Susan (BES) plants. In contrast, N uptake was higher in the BES plants emerging from composts T, F, and Y compared to biochar. It is recommended to minimize concentrated manure-based (e.g., turkey litter) composts for roadside projects as an OM source, and alternatively, enriching wood-based biochar with nutrients when used as a soil amendment. Within the current study, composts such as F and Y were well-suited to establish healthy and long-lasting vegetation.

1. Introduction

Vegetation is a critical component in the context of soil restoration in urban environments. Vegetation establishment effectively alleviates soil erosion and stormwater issues by (1) regulating stormwater flow and reducing runoff volume through rainfall interception, (2) shielding the exposed soil surface from high velocity rainfall, (3) achieving stormwater pollutant removal through phytoremediation, sorption, filtration, and sedimentation, and (4) reducing stormwater export through evapotranspiration (US EPA, 2013; Muerdter et al., 2018). The use of native vegetation (e.g., prairie plants) offers advantages over turf grasses due to their dense and deep root systems (US EPA, 2015; Bloorchian et al., 2016; Hillhouse et al., 2018). As an alternative to mechanical tilling methods, native landscaping can loosen post-construction compacted soils, enhance infiltration, improve stormwater management, and promote biodiversity.

Admixing organic amendments (OAs) into soils stands out as a cost-effective soil quality conservation and restoration technique, promoting vegetation and improving soil structure (Weiss et al., 2005; Olson et al., 2013; Heitman and McLaughlin, 2017; Kranz et al., 2020; Morash et al., 2024; Pamuru et al., 2024). Composts and related OAs increase soil fertility, soil microbial activity, water holding capacity, and infiltration, all of which are drivers of healthy vegetation (Adugna, 2018; Kranz et al., 2020). Organic amendments increase the organic matter (OM)

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https://doi.org/10.1016/j.jenvman.2024.122316
Received 30 May 2024; Received in revised form 26 August 2024; Accepted 27 August 2024
Available online 3 September 2024

content of soils, which is instrumental in improving carbon sequestration and providing soil its health and nutritional quality (Flavel and Murphy, 2006; Wu et al., 2021). In horticulture, use of compost- and manure-based organic soil conditioners have resulted in greater plant productivity and yield (Cheng et al., 2007; Evanylo et al., 2016; Adugna, 2018; Morash et al., 2024). A recent greenhouse study tested two composts for turf establishment, one was a blend of yard waste, food waste, biosolids, and woody materials; the other consisted of yard waste, food waste, and woody materials that were incorporated into a sandy loam soil at increasing additive rates (Kranz, 2021). Biomass production and plant coverage was greater in the compost-amended soils compared to the control treatments. Morash et al. (2024) noted a similar trend where the turf coverage and yield were greater when yard waste compost and biosolids were incorporated into the control soil as OM sources. Other greenhouse and field-based research studies have also observed concomitant improvements in plant establishment due to the addition of organic composts (Garling and Boehm, 2001; Linde and Hepner, 2005; Evanylo et al., 2016; Owen et al., 2021). However, not all composts successfully improve plant yield. Different OA feedstock elements display different effects on plant growth. A recent study that evaluated composts from different feedstock sources showed that nutrient-rich composts (derived from manure or food scraps) enhanced green vegetation and growth; however, compost derived from woody green waste material, due to its low nitrogen (N) content, lowered growth (Heyman et al., 2019). Another greenhouse growth experiment found that adding mulch to the soil resulted in a reduction of turf biomass compared to the control soil (Morash et al., 2024). Additionally, many studies have reported concerns about nutrient leaching typically associated with composts or manure, making it crucial to adhere to the OM requirements for soils (Correa et al., 2006; Owen et al., 2023; Pamuru et al., 2024).

Another widely studied soil conditioner is biochar, a stable carbonaceous byproduct of pyrolysis processes, typically produced at or above 300 °C (Fidel et al., 2017; Lehmann et al., 2011; Oni et al., 2019; USDA ARS, 2021). The sources of biomass used as feedstock (e.g., animal wastes, food scraps, plant debris, wood waste, etc.) and the specific production variables (e.g., pyrolysis temperature and heating rate) greatly affect its structure and stability (Kaya et al., 2022). Biochar addition has proven to be an effective soil remediation strategy as it improves soil porosityand water retention, and, depending on its parental elements, it can also increase the fertility status of soils (Steiner et al., 2008; Agegnehu et al., 2015; Ding et al., 2016). A study by Laird et al. (2010) on mesic types of soil from Iowa showed that cation exchange capacity (up to 20%) and pH of soils increased with addition of biochar. In the field, the addition of charcoal to a fertilized soil was observed to increase N retention in soils and improve its uptake by plants (Steiner et al., 2008). A comprehensive review that synthesized information from 634 biochar-related studies in the context of soil fertility found that, on average, the use of biochar amendment led to a crop yield increase of approximately 20% (Agegnehu et al., 2017). However, similar to observations made with composts, biochar produced from wood-derived sources can lack plant-available nutrients [N and phosphorus (P)], which may limit vegetation growth (Singh et al., 2010; Agegnehu et al., 2017) This underscores the importance of understanding the base properties of composts and biochars to identify the most suitable organic materials that fit the environmental goals of a particular application.

Copious literature (as referenced earlier) is available, centered around establishing fast-growing turf grasses for roadside applications. However, scientific research that focuses on a mixture of native forbs (e.g., *Rudbeckia hirta* L.) and grass (e.g., *Andropogon gerardii* Vitman) species is notably sparse, particularly in the context of OAs. Native species typically have a longer growth period because of their inherent adaptation to thrive in environments with limited resources (Vallano et al., 2012; Shivega and Aldrich-Wolfe, 2017). Therefore, this greenhouse pot study was conducted to test the efficacy of OAs (composts and biochar) in improving the quality of low-grade urban soils to facilitate rapid vegetation growth. In line with the benefits surrounding growing native vegetation, this study also adopted polyculture plantings to provide complementary growth coverage. The goal of this study is to delineate the distinct influences of different OAs when introduced (independently) as sources for OM into four urban roadside topsoils. Furthermore, the study aims to identify the optimal soil-OA blends that satisfy the prerequisites of supplying essential nutrients for accelerated and healthy plant growth and establishing the foundation for soil restoration, by comprehensively evaluating soil properties that lead to enhanced growth. This can help in tailoring the soil amendments as needed in the field to meet the current vegetation goals.

2. Materials and methods

2.1. Soils, amendments and seed mix

2.1.1. Materials

Three sandy-loam soils (as per USDA classification) from active construction sites at Glenwood (G), Sanborn (S), and Clearwater (C) areas and one loam soil from the Ortonville (O) region of Minnesota were collected for this study. Soil source locations and their three textural classifications are presented in Table S1. Fig. S1 shows the grain size distributions (ASTM D6913, ASTM D1140, ASTM D422), and compaction characteristics (ASTM D698) of each material. Examined OAs composed of a wood-derived biochar (B) and composts from various sources: yard waste (Y), food waste (F), and turkey litter combined with green waste (T). The OA manufacturer's information is given in Table S2.

2.1.2. Soil chemical analysis

The following data were collected for the soils and OAs: pH, electrical conductivity (EC), OM content [measured as loss on ignition at 455 °C], N species (Nitrate-N, Ammonium-N, Total N), Mehlich-3 Phosphorus (M3-P), and total carbon. Prior to chemical testing, all soil samples were oven-dried at 55 °C for 72 h and screened through a 2-mm opening sieve. Table S3 shows the soil properties that were measured at the University of Maryland Environmental Engineering laboratories and their test-related information. Furthermore, the soils and the OAs were sent to the Cornell Soil Health Laboratory to analyze for extractable phosphorus (Modified Morgan soil test), predicted autoclave-citrate extractable (ACE) protein (mg extracted/g of soil), and soil respiration (mg CO_2 released/g of soil), the latter two are biological soil indicators (Moebius-Clune et al., 2016). Table 1 presents the summary of the chemical properties of the soils and OAs, respectively.

2.1.3. OA application rates

The OAs were applied to the soils as a function of the soil OM content using Minnesota Department of Transportation (MnDOT) OM criteria for topsoil materials (since the soils were procured from Minnesota). The criterion is a soil OM (by wt%) between 3% and 15% (Standard Specifications for Construction guide,MnDOT, 2020, Section 3877; Test Method: ASTM D2974). The field soils were already within the 3–15% OM range (Table 1), meeting the MnDOT requirements. However, this study aimed to assess the effects of increased amendment rates on plant outcomes, particularly focusing on rapid establishment, even when the soils' nutrient baseline may be considered "adequate" for plant growth. Since high-rate application of composts can lead to unintended consequences such as nutrient leaching (Puppala. et al., 2011; Hansen et al., 2012; Owen et al., 2021, 2023; Pamuru et al., 2024), the soil blends in this study were confined to an upper bound of 10% OM. Each OA was applied to the soil at rates that correspond to target OMs (by wt %) of 5%, 7.5% and 10% for three soils, with the exception of the Ortonville soil which had an average OM content of 5.39% so the application rates targeted the blends of this soil to reach 7.5%, 10% and 13% OM.

Table 1
Chemical analyses of the soils and organic amendments (OAs).

Property	Units	Soils				Organic Amendments (OAs)			
		Clearwater	Glenwood	Ortonville	Sanborn	Biochar	Turkey-Litter Compost	Food-waste Compost	Yard-waste Compost
pH		7.46 ± 0.05	7.45 ± 0.12	7.75 ± 0.03	7.98 ± 0.02	9.42 ± 0.08	6.8 ± 0.07	7.65 ± 0.03	7.52 ± 0.05
EC	μS/cm	453 ± 10.7	335 ± 37	313 ± 46.4	197 ± 3.5	801 ± 46	15,200 ± 440	4730 ± 236	3040 ± 219
OM	%	3.02 ± 0.03	3.76 ± 0.07	5.39 ± 0.11	3.32 ± 0.04	68.9 ± 1.3	41.6 ± 3.59	27.9 ± 1.19	31.7 ± 2.16
C:N[a]		9.5	10.2	9.5	11.5	114	9.3	12.2	13.3
C	%	1.55 ± 0.18	2.22 ± 0.26	2.55 ± 0.04	2.09 ± 0.09	76.7 ± 1.31	24.9 ± 0.4	20.7 ± 0.76	18.4 ± 0.88
N	%	0.16 ± 0.02	0.22 ± 0.01	0.27 ± 0.01	0.18 ± 0.01	0.67 ± 0.03	2.67 ± 0.09	1.7 ± 0.07	1.39 ± 0.08
NH_4:NO_3		1.03	1.6	1.34	7.62	1.65	23.9	1.22	1.23
NO_3-N	mg-N/kg	36.9 ± 0.73	21.2 ± 1.19	42.4 ± 0.54	6.1 ± 0.11	4.32 ± 1.26	29.6 ± 2.56	40.4 ± 18.2	38 ± 12.4
NH_4-N	mg-N/kg	38 ± 0.6	33.9 ± 0.71	57 ± 4.36	46.5 ± 1.76	7.14 ± 3.68	706 ± 74.4	49.2 ± 3.5	46.8 ± 3.09
M3-P	mg-P/kg	54.2 ± 0.44	32.4 ± 1.16	45.3 ± 0.47	26.6 ± 1.13	657 ± 7.65	3899 ± 256	655 ± 68.9	662 ± 48.9
Extractable P[b]	mg-P/kg	5.2	1.7	4.9	6.5	599	4841	650	573
ACE Protein[b]	mg/g	4.7	4.6	5.3	4.4	0.3	85	63.3	33.6
Soil Respiration[b]	mg/g	0.4	0.5	0.4	0.6	0.7	2.3	2.6	2

All values are denoted as Mean±SD of three representative samples.
[a] C:N and NH_4:NO_3 ratios are calculated using the means of C% & N% and NH_4 & NO_3, respectively, hence SD is not included.
[b] Measurements for extractable P (Modified Morgan soil test method) and biological indicators obtained from Cornell Soil Health Laboratory.

2.1.4. *Seed mix*

A seed mix comprised of graminoids (grasses) and forb (flowers) species native to Minnesota was selected for this study. Diversity of native species can promote habitat and climate resiliency and are well-suited for short-term vegetation establishment due to their adaptability to local conditions. The seeding rate was guided by MnDOT's native Seed Mix 35–241, which is intended for general roadside use (MacDonagh and Hallyn, 2010). MnDOT's typical range for native mixes range between 3.9 and 4.9 g/m^2 for common upland seed mixes. Information pertaining to the plant species of the seed mix, their individual seasonal preferences (warm vs cool), and application rates is given in Table 2.

2.2. *Pot experiments*

2.2.1. *Pot preparation*

A total of 156 (25.4-cm in diameter and 23-cm in height) pots (4 controls + 4 soils x 4 OAs x 3 OA rates, prepared in triplicates) were assembled in the University of Maryland's research greenhouse complex. Each pot contained two layers: a 5.1 cm subsoil (compacted) layer at the bottom and a 10.2 cm fertile layer above the subsoil (Fig. S2). The subsoil layer consisted of the unamended soil, compacted to its maximum dry density. Maximum dry densities of the study soils (Table S4) were determined by following the standard Proctor procedure (ASTM D698). The subsoil layer was placed to ensure that the seeds and the soil were contained within the pot, attempting to mimic field conditions. The fertile layer composed of soil amendment blends (using the same soil as in the subsoil layer, albeit amended) under investigation for vegetation establishment.

Table 2
Composition of species included in the seed mix.

Seed Name	Scientific Name	Season	Percent in Mixture (wt %)	Seeding Rate (g/m^2)
Big Bluestem (Native)	*Andropogon gerardii* Vitman	Warm	20	0.79
Indian Grass (Native)	*Sorghastrum nutans* (L.) Nash	Warm	20	0.79
Slender Wheatgrass (Native)	*Elymus trachycaulus* (Link) Gould ex Shinners	Cool	30	1.23
Kalm's Brome (Native)	*Bromus kalmia* Gray	Cool	20	0.79
Black-Eyed Susan (Native)	*Rudbeckia hirta* L.	Cool to Warm	5	0.22
Purple Prairie Clover	*Dalea purpurea* Vent.	Warm	3	0.11
Canada Milk Vetch	*Astragalus canadensis* L.	Warm	2	0.11
Total			**100**	**4.04**

Mixing Organic Amendments (Fertile Layer): The bulk densities of the composts and the biochar were determined as described in the protocol by Washington State University (WSU, 2022). For measuring the soil bulk densities, a 10.2 cm depth from the surface of the subsoil layer was delineated. Plant debris (roots) and rocks (>2.54 cm) were separated from the soils to the extent feasible. Afterward, the soil was carefully placed into the pot and evenly spread until it reached the marked 10.2 cm depth. The corresponding soil mass was measured for calculating bulk density. The bulk densities, along with the OM contents of the soils and the OAs are provided in Table S4. Using these parameters, a mass balance equation (Eq. (1)) was formulated to determine the ratio of the volume of OA to soil required to achieve the specific OM target in the soil-OA blend.

$$\frac{V_{OA}}{V_s} = \frac{\rho_s(\theta_t - \theta_s)}{\rho_{OA}(\theta_{OA} - \theta_t)} \tag{1}$$

where V_{OA} is volume of OA added to soil-OA mix, V_s is volume of soil in the soil-OA mix, ρ_{OA} is bulk density of OA, ρ_s is bulk density of soil, θ_{OA} is OM of OA, θ_s is OM of soil, and θ_t is target OM of the soil-OA blend.

Seed Application: Prior to seeding, pots were randomly ordered and no two replicates or soils of the same kind were adjacently placed. Next, the pots were watered enough to moisten the soil before planting the seeds. A seeding rate of 4.04 g/m^2, equivalent to 0.21 g of seed mix per pot, was applied and gently pressed into the soil by hand to achieve good soil-to-seed contact. The seeds were pre-mixed in bulk at the rates shown in Table 2; therefore, given the small amount (0.21 g) of seed mix that was added, each pot may not have each seed type uniformly applied due to the relatively small amount that were spread.

2.2.2. *Experimental conditions and watering*

In general, warm-season grasses typically require temperatures between 27 °C and 35 °C during the growing season, while cool-season grasses can thrive in temperatures between 18 °C and 24 °C. Thus, throughout the experiment, the inside temperature of the greenhouse rooms was maintained at 23 °C–25 °C during daytime and 17 °C–19 °C at night, with a 14-hr photoperiod. Watering events occurred three times a week, for a total of 1.6 cm (~800 mL) per week, corresponding to an annual precipitation rate of 81.3 cm in Minnesota. Additional water was provided on certain days when it appeared that the plants and the soil in the pots were excessively dry.

2.2.3. Pot study growth measurements

Green Coverage: The pot experiment spanned for 15 weeks (105 days) after seeding and was conducted during the fall season (Aug to Dec 2022). Images of the pots were captured bi-weekly, starting from week 3 until week 15, in a custom-built image station (Fig. S3). LED lights were used to ensure adequate and consistent lighting for capturing high-quality images.

To analyze the images for percent green coverage (%GC), a digital image-based software ***Canopeo*** was utilized with default settings of Red/Green (0.95), Blue/Green (0.95) and Noise reduction (100) (Patrignani and Ochsner, 2015). This application converts the green parts of an image to white pixels and the rest of the image area to black. The output is represented as %GC in this study. Fig. S4 details the image processing steps that were followed for estimating %GC. Prior to inputting (Fig. S4a) into *Canopeo*, the images were preprocessed in Adobe Photoshop (2022), where they were cropped along the inner diameter of the pot and then as an inscribed square that measures the same edge as the pot diameter (Fig. S4b). Since the black-eyed Susan (BES) plant species produced yellow blooming flowers, to prevent underestimation of the %GC, they were manually painted green (Fig. S4c) as *Canopeo* does not read yellow color. The final measured area is displayed in Fig. S4d.

Growth Assessment: Dry biomass, growth index, plant N, and leaf area were employed as end-of-study growth parameters. After capturing the final set of pot images (with and without volunteer vegetation, e.g., weeds), plant measurements relevant to the growth of BES were taken. BES was the dominant plant species alongside grasses in the pots. In addition, different amendments clearly had different influences on the morphology of the BES plants. This prompted a more detailed examination of the BES plants in this study. The Growth Index (GI) is a three-dimensional parameter calculated as the average of the widest width, perpendicular width, and height of a BES plant (Norcini and Aldrich, 2003); GI of the healthiest looking BES plant per pot was determined. Growth in media with different OAs produced variability in the color and area of the BES leaves (Fig. 1). Therefore, plant N and leaf area were determined on the same BES plant that was evaluated for GI. Plant N was measured by a PlantPen/N-Pen N110 reflectance-based instrument which correlates the chlorophyll (Normalized Difference Greenness Index, NDGI) and nitrogen contents in a plant to estimate "%N". Leaf area of the BES plants was measured using a LI-3100C Area Meter. Snipped leaves of the healthiest BES plant per pot were spread on the conveyer belt of the instrument, which then initiated a rotational scan to measure the combined or cumulative leaf area. Finally, final above-ground biomass (weeds not included) was measured by harvesting the vegetation at the soil level, transferring the shoots into brown paper bags and oven-drying at 50 °C for 48 h. After drying, the plant material was weighed to report dry plant biomass (USDA NRCS, 2022).

2.3. Statistical analysis

Data were collated in Microsoft® Excel (version 16.87), then imported, preprocessed, and analyzed in Python (version 3.12.4). To determine the statistical significance of amendment type and rate on each plant measurement, a two-way analysis of variance (ANOVA) was performed at a 95% confidence level across all soil types. Multivariate Analysis of Variance (MANOVA) was leveraged to assess the collective effect of amendment type and rate on multiple plant metrics (dependent variables). Post-hoc analysis using Tukey's Honest Significant Difference (HSD) test identified significant differences among amendment-rate combinations. The mean performance of each combination (amendment type and rate) across all plant metrics was calculated to rank the amendments for each soil type. Additionally, the overall best amendment and rate was determined by ranking combinations based on their aggregated performance metrics. Mean values for the replicates and error bars denoting the standard deviation are presented as bar plots and correlation plots. Linear relationships were determined by Pearson's correlation (R), and the regression analysis was carried out at alpha = 0.05 to determine the probabilistic significance (p) value.

Fig. 1. Differences in color, length, and leaf area of the black-eyed Susan (BES) plants between soil blended with turkey litter (T) compost (left pot) vs soil blended with biochar (right pot).

3. Results and discussion

3.1. Changes to soil pH, EC, and OM

Soil pH, EC, and OM were measured for all 52 different soil blends (including replicates) that were prepared (see Table S5). A significant increase ($p < 0.001$) in soil pH was observed when the B amendment was incorporated; the pH of soil-biochar blends ranged from 7.84 to 8.47 (Table S5). This liming effect is due to the primary presence of carbonates and surface organic functional groups in biochar, which collectively contribute to its high pH (Fidel et al., 2017). The T amendment also led to an increase in the pH of the soils (except in Sanborn), despite having a slightly acidic pH of 6.8 ± 0.07. When an ammonium source such as the T amendment is introduced into the soils, the ammonium will be released and converted to ammonia gas, which can form ammonium hydroxide (NH_4OH) in the soil solution, consequently increasing the soil pH (at least temporarily) (Pan et al., 2016). In contrast, the pH in compost-based F and Y amended soils remained largely unchanged ($p > 0.05$), as they possessed a slightly alkaline pH of 7.65 ± 0.03 and 7.52 ± 0.05, respectively.

All three composts (Y, F, and T) statistically increased ($p < 0.001$) the EC in all soils, while biochar showed no noticeable effects. The most substantial increase in EC was due to the T amendment, increasing soils EC by a factor of 2.9–22.7 times. This was followed by the F amendment (17–725% increase) and Y (4–428% increase) (Table S5). Compost sources naturally contain soluble salts and tend to increase soil EC when incorporated, with the magnitude depending on the feedstock (Li-Xian et al., 2007; Gondek et al., 2020).

3.2. Green coverage (%GC)

Fig. 2 demonstrates the temporal (biweekly) %GC patterns of the vegetation for the various soils and their OA blends. A sigmoid function

(Eq. (2)) was nonlinearly regressed to the plant coverage data using the *nlinfit* function in MATLAB's Statistics and Machine Learning toolbox to quantitatively analyze the growth patterns.

$$y = K_1 * (1 + \tanh(K_2 * (x - K_3))), \quad (2)$$

where $K_1, K_2,$ and K_3 represent half the maximum coverage (as %), the rate of growth (in weeks^{-1}), and the half-life (the time at which half the maximum coverage is achieved, in weeks), respectively. The variables y and x denote %GC and the growth time in weeks, respectively. A combination of high K_1 and K_2 and low K_3 suggests a greater and quicker establishment of plant cover. Table S6 presents the data related to the regression constants (K_1, K_2, K_3) estimated for each soil type. Weeds were eliminated from the pots before estimating the final coverage on the 15th week, while the preceding weeks included them. This approach was taken to specifically understand the effects of OAs on the seeded vegetation. Additionally, the preprocessed images were cropped along the pot's inner diameter, meaning the coverage outside the pot was not accounted for. Therefore, the analysis shown in Fig. 2 should be deemed as underestimates in comparison to the "true" vegetation coverage.

3.2.1. Effects of organic amendments (OAs) on green coverage (%GC)

Ortonville (O): The naming convention for soils, for example 'OT1', is structured as follows: the first letter indicates the soil type (Ortonville), the second letter represents the amendment type (turkey litter and green-waste based compost), and the third character indicates the application rate (rate 1). The greatest final mean coverage (84.9 ± 9.85%) was observed in the OF1 soil followed by OB3 (82.4 ± 5.47%), OY2 (77.2 ± 21.77%) and OB1 (73.1 ± 18.56%) (Fig. 2 and Fig. S5). The growth curves of the OY blends displayed delayed growth patterns (higher K_3) compared to the control soil "O", particularly within the initial 9 week-period (Fig. 2). However, for two of the OY blends, OY1 and OY3, K_2 (rate) was larger than that of the soil "O". The F compost, at lower application rate 1 (7.5%), also showed a delay in growth initially but later gained momentum as vegetation started to establish and eventually outcompeted the control. Rates 2 (10%) and 3 (13%) of the F compost, exhibited overlapping plant coverages, but produced less vegetation compared to control "O" throughout the study. In contrast, the T compost failed to yield any plants at higher application rates (7.5% and 10%) even after 15 weeks of seeding. At rate 5%, the T compost produced a few grass strands with time, covering only 17.4 ± 10.14% of the soil surface after the 15-week period. Alternatively, biochar was the only OA (regardless of its application rates) that outcompeted the control in terms of %GC. While biochar appeared to enhance coverage when mixed into soils, the %GC was not entirely contributed from the planted native species, but rather from the prevalence of weeds, such as *Chenopodium album* and/or Yellow Wood Sorrel. Although *Chenopodium album* rapidly grew in the earlier stages, after week 9, these species started to wither in the soil-biochar mixes. Nevertheless, %GC without weeds decreased from week 13 to week 15 in the soil mixes (Fig. 2). Since this loam soil already had an OM content of 5.39% (which is high for organic soils), adding the organic amendments (OAs) did not significantly improve plant coverage.

Clearwater (C): The control's (C) coverage at the final week was 87.6 ± 5.91% (Fig. 2 and Fig. S5). Growth curves indicated that the B, F and Y amendments consistently exceeded the %GC of the control at least through week 11. This was further substantiated by the nonlinear regression constants, which exhibited lower K_3 values (indicating a shorter half-life) in comparison to the control C (K_3 = 8.82 weeks), with

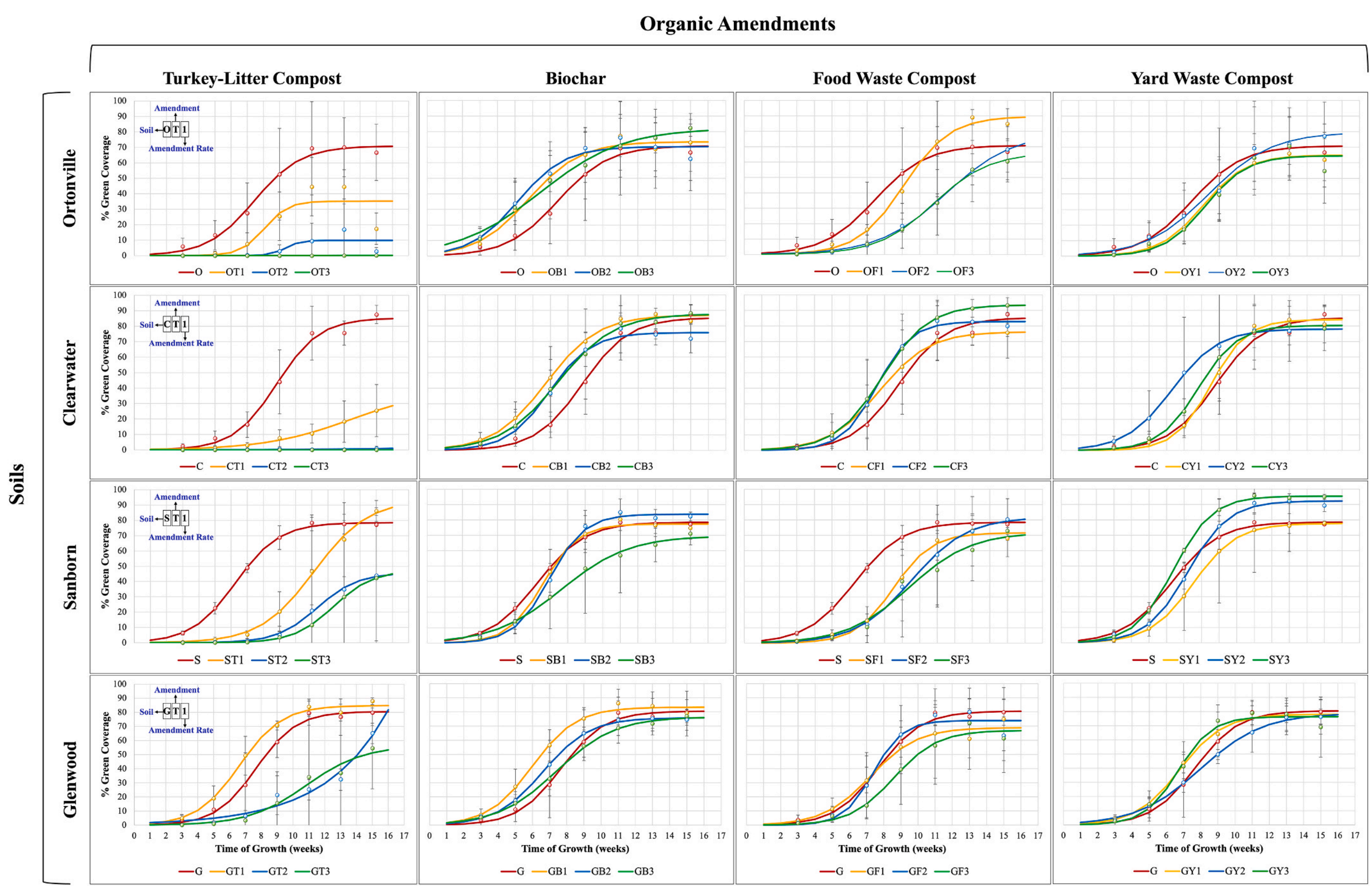

Fig. 2. Temporal changes in %GC of soil-OA blends. For Sanborn, Clearwater, and Glenwood soils, rates 1, 2, and 3 correspond to target soil OM of 5%, 7.5%, and 10%, respectively. For Ortonville, these rates are 7.5%, 10%, and 13%.
Note: Weeks 3–13 included weeds in the %GC analysis, while week 15 did not.

K_1 ranging from 37.9% to 46.7% for plant growth originating from B, F, and Y amended soils. Furthermore, among these amendments, the K_3 for vegetation growth from C-biochar mixtures was the lowest. Consistent with the observations of Ortonville-T soils, the worst Clearwater blends contained the T amendment. Grass strands were again the only species collected from the CT1 blends with 25.4 ± 16.8% GC, and at higher T application rates (CT2 and CT3) 0% GC was seen throughout the study. Clearwater soils had weeds (cleavers) during the study period. However, since cleavers did not densely cover the soils as *Chenopodium album* did in Ortonville, the presence of weeds in the Clearwater blends had a relatively minor impact on the %GC throughout the experiment. Despite this, cleavers were excluded from the plant analysis at the end of the study.

Sanborn (S): The Y amendment at rates 2 and 3 had the greatest influence on the Sanborn soil, with SY2 and SY3 yielding 12.3% and 17.9% (respectively) more GC compared to the control S at 15 weeks (Fig. 2 and Fig. S5). This was further supported by the Y regression constants, K_1 and K_2, which were higher than S, signifying greater coverage and rate. In the case of F amended Sanborn soils, initial plant growth was observed only after week 5, but soon after climbed to 67.9 ± 11.82%, 80.3 ± 13.5% and 72.7 ± 2.32% GC for SF1, SF2 and SF3, respectively, by week 15. Similar to the patterns noted in the Ortonville-F blends, the F compost slowed the vegetation establishment when added to the soil; the higher its application rate, greater was the delay. The T amendment also slowed seed germination and growth response (Fig. 2), with the final %GC of the ST1 blend being 86.1 ± 6.9%, placing it right below SY2 and SY3 at the end of the study. Additionally, the ST2 and ST3 growth was slower than ST1; but in one of the replicates of each of these soils, the BES surfaced along with other grass species. This led to improved %GC of 43.9 ± 44.3% for ST2 and 42.3 ± 41.0% for ST3, albeit with considerable variability. The growth curves resulting from the B amendment at rates 1 and 2 are not different from that of the control soil S. However, at rate 3, the established vegetation coverage and rate decreased. Only 3 out of the 39 Sanborn pots (including replicates) developed weeds (yellow wood sorrel and Canada thistle) which therefore did not contribute to the %GC estimates of these soils.

Glenwood (G): GT1 is the only amended Glenwood soil that demonstrated greater %GC (87.8 ± 2.41%) than its control counterpart, G (79.6 ± 8.99%) by the end of the study (Fig. 2 and Fig. S5). All other combinations of Glenwood and OAs produced lower above-ground plant coverage than G. Notably, when the T compost was added Glenwood at rate 1, it did not experience any growth delays unlike ST1, CT1, or OT1, and emerged successful in enhancing this soil for plant growth. GT2 and GT3 yielded 65.1 ± 7.25% and 54.4 ± 28.64% GC, respectively, again greater in amount compared to the corresponding T rates of other soils. The pattern was uniform across all soil types: as the application rate of T increased, plant yield decreased. The incorporation of biochar at rate 1 improved the speed of plant establishment; the half-life, K_3, for GB1 was 6 weeks (K_1 = 41.7%), in comparison to 7.68 weeks for G (K_1 = 40.3%). Canada thistle was the weed species that prevailed in the Glenwood soils. Coverage dropped between week 13 and week 15 in the soil mixes after removing the weed species (Fig. 2).

3.2.2. Correlation between growth and soluble salts content of the soil-OA blends

From the biweekly %GC analysis (growth curves), it was observed that the compost amendments either contributed to delayed or suppressed growth. The latter was particularly noted with the T amendment. To investigate the dependence of plant response to soluble salts levels in the media, the EC of all 52 soil blends measured at the onset of the experiment was plotted against the %GC for every two-week period (weeks 3, 5, and 7, Fig. 3). In this figure, the means of %GC and EC are shown, but error bars are only added to %GC and not EC for better legibility. A trending exponential decay is observed for the coverage with an increase in the EC content of the soils in the first 7 weeks of seeding; the p-value was determined after log transforming the coverage data and a linear regression was obtained. Although the scatter of the data points is low ($R^2 < 0.6$), a strong statistical correlation ($p < 0.00001$) between the salts content and coverage was noted in the first 7 weeks. As %GC expanded, a linear model was found to be best suited for the data for weeks 9, 11, 13 and 15 (plots are not shown for brevity), with the correlation of determination (R^2) increasing over time along with high statistical significance ($p < 0.00001$). This switch from exponential to linear correlation between %GC and salts is postulated to have occurred because, with each watering event, the salts would leach from the root zone, making the topsoil layer more favorable for seed germination and growth. Many seeds need soil conditions with an EC < 4000 μS/cm for germination (Gondek et al., 2020). To test this, soil EC measurements were taken at the end of the experiment, after plant harvest, for soils amended with T compost (Table S7), indicating a decrease in rhizosphere EC after 15 weeks. Previous studies have also noted that compost and compost-like organic amendments release salts from the soils during rainfall, irrigation or leaching events (Tazeh et al., 2013; Wu et al., 2018; Pamuru et al., 2024; Pamuru, 2024), corroborating the pot study findings. Leaching saline soils can reduce soluble salts concentrations, allowing plants to grow without having to withstand the associated stresses (Qadir and Oster, 2004; Gondek et al., 2020).

Fig. 4 offers visual evidence showing the best and worst performing soil-OA blends for plant establishment. Clearwater soil amended with T at rate 3 (CT3) did not produce any yield because of a soluble salts (EC) value of 5137 ± 37.9 μS/cm, even after 15 weeks of seeding. In contrast, Y displayed full-blown coverage when amended into Sanborn at rate C (SY3; EC = 1039 ± 9.3 μS/cm). In general, excess salinity in a soil rhizosphere prompts greater osmotic pressure, thereby limiting the water and nutrient uptake of plants (Hasanuzzaman and Fujita, 2022); soils with an EC less than 2000 μS/cm are considered non-saline, while those with an EC greater than 4000 μS/cm are generally considered slightly saline (USDA, 2011a). By extension, in this study, soils with initial EC greater than 2000 μS/cm restricted plant production to <50% coverage even by week 15.

Mature compost generally has plant-ready nitrogen (NH_4:NO_3 < 1:1), low salts (EC < 2000 μS/cm), and a pH between 6 and 7.5 (Radovich et al., 2011). T is a concentrated, manure-based compost, which has a high soluble salts concentration (EC = 15,200 ± 440 μS/cm), high NH_4-N (706 ± 74.4 ppm), and high NH_4:NO_3 ratio (24:1) (Table 1). Impacts of ammonium toxicity and salt stresses on plant response are well-documented when poultry litter is applied (Lu and Edwards, 1994; Pan et al., 2016). Also, soil pH increased when the T amendment was added to the soils (Table S5). This combination of high pH and presence of ammonia gas halts the two-step nitrification process ($NH_4 \rightarrow NO_2 \rightarrow NO_3$) at the nitrite stage; this leads to an accumulation of nitrite in soils and can be detrimental to seedlings, particularly in dry and well-aerated soils (Breuillin-Sessoms et al., 2017; Venterea et al., 2020). Experiments conducted at varying ratios of NH_4:NO_3 demonstrated an impairment of the plant species when NH_4-N was the only supplemental N nutrient and greater plant development and yield occurred under sole NO_3-N inputs (Saloner and Bernstein, 2022). Zhang et al. (2019) suggest a NH_4:NO_3 ratio of 25%:75% for desired root biomass and nutrient uptake in *Capsicum annuum* L., signifying a preference for soils with lower NH_4 levels compared to NO_3 to enhance plant productivity. Overall, the higher amounts of salts and ammonium in T seem to have hindered plant growth and development at higher application rates (rates 2 and 3).

3.3. Plant biomass and growth index

Ortonville: The T amendment was the only OA in Ortonville soil that did not grow plants. Biomass production from all amendments and application rates showed reduced growth compared to the control, O, except for OF1 (Fig. 5). Weed presence was not reflected in the above-

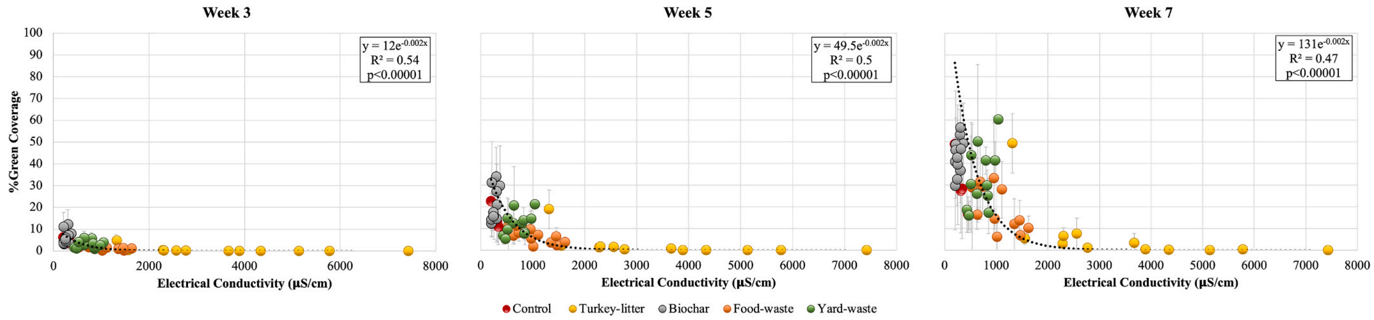

Fig. 3. Influence of initial soluble salts (EC) from pre-seeded soils on the green coverage of the studied blends during 3, 5, and 7 weeks. Specific colored dots represent a particular OA mixed into the soils.

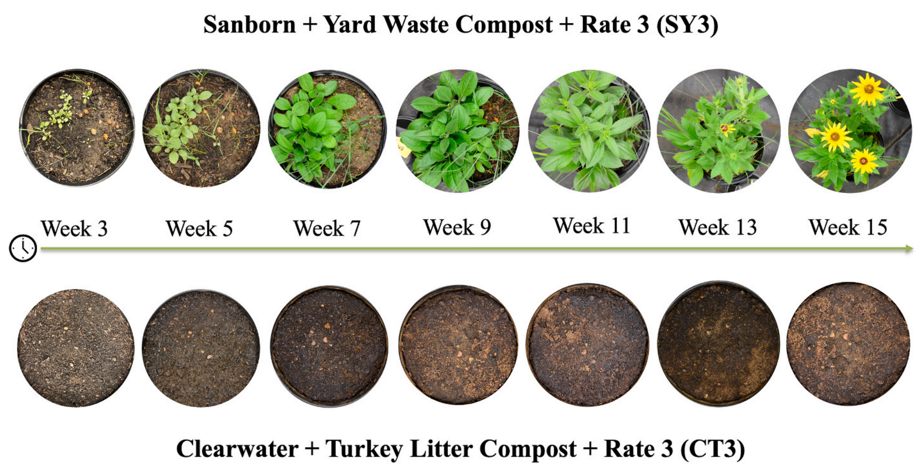

Fig. 4. Comparison between one of the best vs worst performing soil-OA blends for vegetation establishment.

ground biomass, because the measurements did not include them. The growth index of BES plants from the Ortonville soil mixes provided similar findings to biomass; the GI did not improve when OAs were added to this soil (Fig. 6). Since unamended Ortonville contains an acceptable level of OM (5.39%), it provides greater plant available nutrients than other soils. Thus, OAs influence on biomass and GI were not clearly observed.

Clearwater: Food waste compost applied at rates 7.5% and 10% (CF2 and CF3) yielded 42.3% and 80.1% more plant biomass compared to the reference soil (C). This increase was followed by CB1 (26.9%) and CY2 (16.3%), with other amendments showing an increase less than 10%, or reduced growth. The greatest improvement (28.8% increase) in the GI in Clearwater occurred when biochar was amended at rate 2. Consistent with biomass, CF2 and CF3 soil blends positively contributed to an increase of 17.5% and 22.1% respectively in the GI when F was added to the soil. Overall, Clearwater benefitted the most from the F amendment compared to other OAs.

Sanborn: The Y amendment increased the vegetative biomass at higher application rates by 1.8× for R2 and by 1.92× for R3 compared to the control, S. T at lower rate (5%) also enhanced above-ground productivity, while higher rates (7.5 and 10%) stunted growth. However, these high rates of the T amendment produced some biomass (~4.4 ± 5.6 and 4.3 ± 5.4 g respectively) by the end of the study. Sanborn-T blends contained lower salts content compared to the corresponding Ortonville- and Clearwater-T blends. Consequently, they offered a more favorable environment for plant growth. Although the biomass production was the greatest in SY2 and SY3, the GI of BES plants in these pots did not show statistical improvement ($p > 0.05$) compared to the

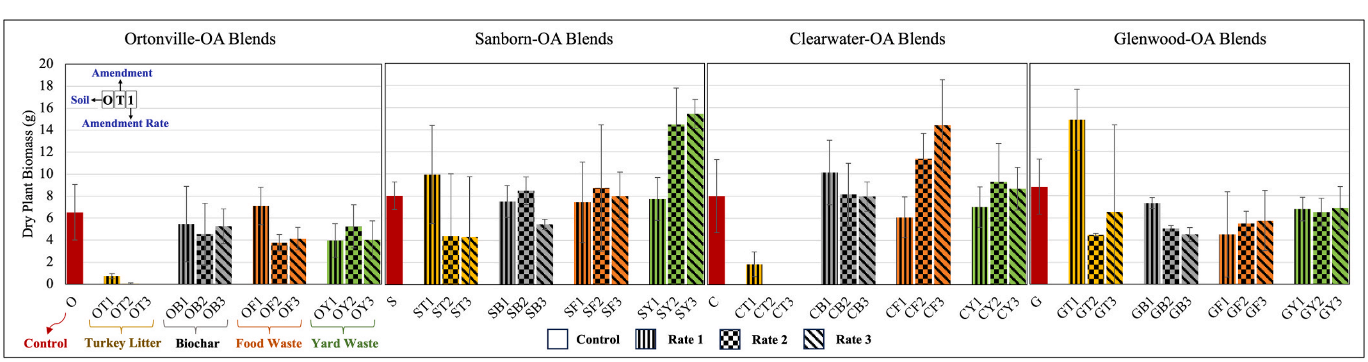

Fig. 5. Dry plant biomass (grams) in soil-OA blends. ANOVA showed significant effects ($p < 0.05$) due to amendment type for Ortonville, Sanborn, and Clearwater, but not for Glenwood ($p > 0.05$).

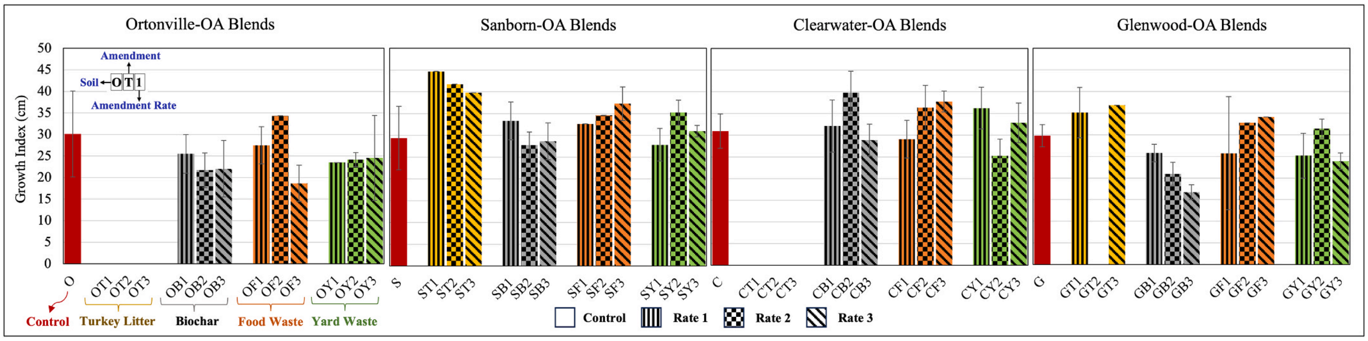

Fig. 6. Growth Index (in cm) of black-eyed Susan from soil-OA blends.
Note: BES was only produced in one of the three replicates for OF2, ST1, ST2, ST3, SF1, SF2, GT3, GF2, and GF3. Therefore, error bars were not included, as the other two replicates were not treated as zero values. This approach was used to emphasize the impact of the amendments on GI quality in these soils whenever BES production occurred.

control soil (S) (Fig. 6). However, the GI was positively influenced (ST1, 52.1%; ST2, 42.1%; ST3, 35.4% increase compared to S) by the addition of T. This suggests a morphological advantage to plants when soil is mixed with a high nitrogen amendment, as long as the OA additive rate does not lead to excessive amounts of salts and ammonia.

Glenwood: Except for GT1, which increased the BES GI by 18%, all other soil blends had a negative influence on biomass production in the Glenwood soil (Fig. 5). The biochar OA decreased yield by 16.8%, 43%, and 49% at rates 1, 2, and 3, respectively, compared to the control soil (G). Typically, amendments with greater than 24:1 C:N ratio immobilize N in the soil, reducing the plant available fraction (USDA, 2011a). Biochar fits this paradigm, and amending soils with biochar increases the C:N ratio. The biochar used in this study has a C:N ratio of 114:1, in stark contrast to the baseline C:N ratio of 10.2:1 found in the unamended Glenwood soil (Table 1). Unexpectedly, F and Y also developed plant biomass that was 34.9–49% and 21.9–26.2%, respectively, lower compared to G. Although a similar trend of suppressed growth was observed when composts were mixed into the Ortonville soil, the amendment rates for Ortonville were higher compared to Glenwood, Sanborn, and Clearwater.

3.4. Plant nitrogen and leaf area

Fig. 7 shows bar plots of %N in the leaves of BES across the soils. Although plant N content was also measured for the grass species in each pot, only the uptake of BES is discussed here as the general trends remained the same between the two groups. Absence of SD error bars on some soil blends (e.g., ST1, ST2, ST3 etc.) indicate that only one of the three soil replicates produced BES. The N% in the OAs is T = 2.67 ± 0.09%, F = 1.7 ± 0.07%, Y = 1.39 ± 0.08% and B = 0.67 ± 0.03% (Table 1). For most B-amended soils, the BES showed reduced average leaf N (also visually less green, Fig. 1) compared to other OA mixes and controls (except Sanborn) (Fig. 7). Sanborn soil contained 0.18% N and the lowest plant available nitrate; this lack of plant nutrient manifested in the BES leaves of the control soil (S), producing the lowest plant N (2.3%) (Fig. 7). Typically, less than 3% N in plants can induce deficiencies and affect the quality (Mills and Jones, 1996; Morash et al., 2024). In this study, all soils amended with biochar exhibited N deficiencies, with the average uptake levels remaining below 3% (Fig. 7). Although biochar produced greater plant coverage in the initial stages of growth, the health of the vegetation (yellowing of leaves, crispy edges, etc.) declined over time, which could be attributed to the poor uptake of macronutrients such as N. Moreover, biochar can also hinder the translocation of P and micronutrients from root to shoot as they get tied up to the organic compounds in the rhizosphere (Alkharabsheh et al., 2021). Of the composts, for at least one rate of application, the BES %N in Y-soil was less than ($p < 0.05$) the corresponding value for F- and T-soil of any soil (Fig. 7). Alternatively, the higher plant available N (NH_4+NO_3) content from the T compost prompted the greatest N uptake in the BES plants and grasses of Glenwood- and Sanborn-T amended soils. Saloner and Bernstein (2022) also reported higher N accumulation in cannabis plant with increased NH_4 and NO_3 supply.

The autoclave-citrate extractable (ACE) protein index serves as a soil indicator that can offer beneficial insights into the organic N fraction that can be mineralizable into plant N over time (Hurisso et al., 2018; Geisseler et al., 2019; Sainju et al., 2022). In this study, among the OAs examined, the ACE index is the lowest for B (0.3) and the highest for T (85). The Cornell Soil Health Lab assigned a low-quality rating of 2/100 for B and 100/100 for all three composts in terms of their ACE content. It is noteworthy that, despite plant species emerging in biochar-amended

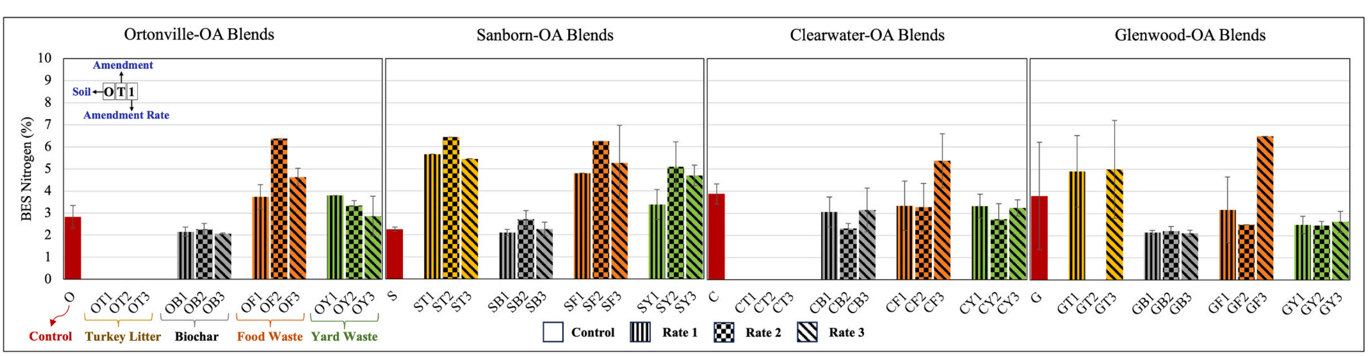

Fig. 7. Plant Nitrogen (%) of black-eyed Susan from soil-OA blends.
Note: BES was only produced in one of the three replicates for OF2, ST1, ST2, ST3, SF1, SF2, GT3, GF2, and GF3. Therefore, error bars were not included, as the other two replicates were not treated as zero values. This approach was used to emphasize the impact of the amendments on BES plant N% in these soils whenever BES production occurred.

soils, the overall health of the vegetation was subpar, as demonstrated by the N uptake results. The growth of vegetation in biochar soils can thus be attributed to the inherent traits of native vegetation, which are adapted to survive under nutrient-limiting conditions (Shivega and Aldrich-Wolfe, 2017).

Typically, an increase in the application rate of N should have a positive effect on the morphology of the leaves, i.e., leaf size (length, width, and area) (de Ávila Silva et al., 2021). Taking this lead, the total leaf area of a BES plant with the sturdiest stem per pot was measured. Fig. S6 presents the total leaf area data for the amended soils. Similar to the observations made in the N% analysis, the N content of the amendments also influenced the leaf area of the BES species. It should be noted that smaller leaf areas, particularly seen in the compost-amended soils, do not necessarily represent the full potential of the growth, because in some pots (e.g., OF3) the BES experienced delayed growth. Visual observations identified smaller leaves and thinner stems of the BES plants from the biochar-amended soils compared to the compost-amended soils (Fig. 1). Only two soils (Sanborn and Glenwood) when amended with T grew BES, and the leaves of these plants looked greener and larger compared to other soils.

The plant uptake of nitrogen is plotted against the pot leaf area index (LAI) to emphasize the correlation between the two parameters (Fig. 8). LAI is a ubiquitously used dimensionless quantity that measures one-sided leaf area per unit ground surface, typically of a canopy (Fang et al., 2019). In this study, the pot LAI is calculated by dividing the total foliage (or leaf area, in cm^2) of the healthiest BES plant in each pot by the surface area of the soil in the pot, which is 507 cm^2. Only 44 out of the 52 blends were considered since 8 of those did not produce any BES plants. Fig. 8 demonstrates that plant N is linearly related ($p < 0.00001$) to the plant LAI. Evidence from past research also noted correlations between leaf area index and the N concentrations in different plant species (de Ávila Silva et al., 2021; Lemaire et al., 2007; Yin et al., 2003). Plant N enhances chlorophyll production, leading to greater leaf expansion and a higher LAI. This correlation is critical because the LAI is directly linked to the plant's ability to produce energy through photosynthesis and improve plant health.

3.5. Optimum mixing ratios for vegetation growth

The experiment revealed the various effects of OAs on plant growth and health, with some effects being nuanced while others were more pronounced. To better understand and quantify the overall impact of these amendments across four different soil types, each amendment and application rate was ranked from best to poorest based on the mean performance of the plant metrics. Fig. 9 presents a performance matrix, illustrating the relationships between the study's dependent variables (plant outcomes) and independent variables (amendment type and rate). For BES LAI, %N, and GI any soil that did not produce BES plants was assigned a value of zero to prevent artificially inflating the rankings.

The results demonstrate that yard waste compost consistently ranked within the top three across all plant outcome categories, with food waste compost closely following. In contrast, turkey litter compost generally occupied the lower ranks in all categories. The performance of biochar was more variable; higher application rates (R2 and R3) were less favorable to plants compared to the lowest rate (R1). The goal of amending the soil is to improve the soil environment to facilitate desired (rapid and healthy) yield through OA addition. If OAs cause soil conditions to deviate from the "optimum", plant production can be negatively impacted. Typically, a neutral pH, non-saline conditions, low ammonium, high soil protein index, and an adequate C:N ratio are required to stimulate and sustain plant growth. Of the four amendments, only yard waste compost consistently met these criteria; in this study, higher application rates of yard waste compost, within the range used, correlated with improved plant growth. Food waste compost also proved effective, though its N and salt levels were at the upper end of the optimum spectrum, potentially delaying plant establishment. Biochar contained low nitrogen and high carbon contents, while turkey litter compost had excess nitrogen (in the form of ammonium) and high salt concentrations, making these two OAs impair or stunt growth, specifically at higher application rates.

4. Conclusions

Three composts (T, F, and Y) and one wood-based biochar (B) were evaluated for promoting rapid and dense native vegetation growth in four topsoils removed from active construction areas. While it is difficult to recommend optimum soil-OA ratios based on these data, the findings offer guidance on selecting the right OA based on information about the amended soils that contributed to poor growth.

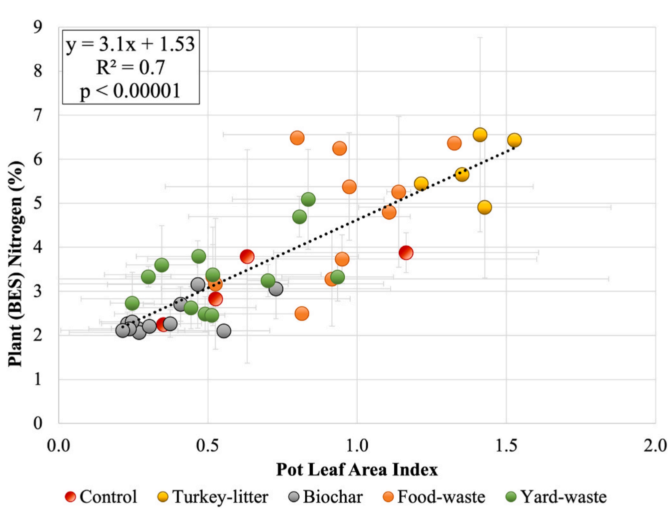

Fig. 8. Correlation between plant nitrogen and leaf area index (LAI) of the black-eyed Susan (BES) plants. Specific colored dots represent a particular OA mixed into the soils.

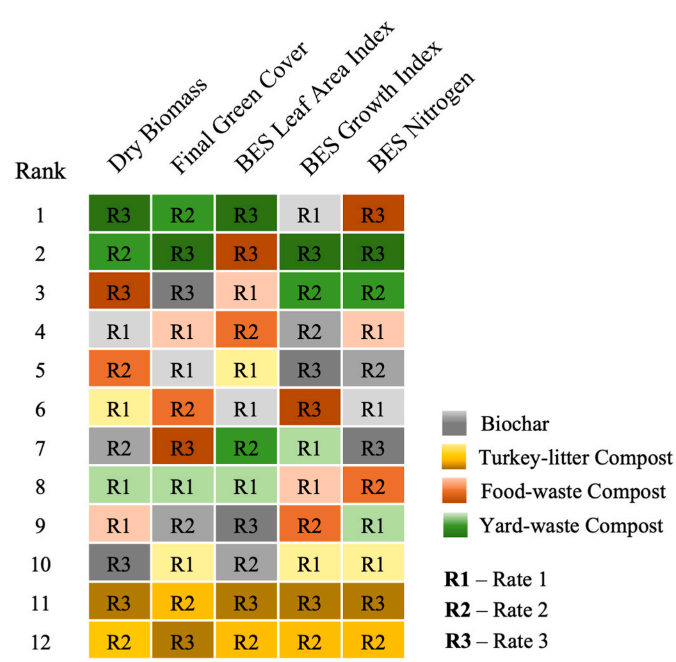

Fig. 9. Ranking of all amendments and application rates by individual plant metric across all soil types.
Note: MANOVA results indicated that across all soil types, the amendment type consistently showed significant ($p < 0.05$) effects on all plant metrics.

1. *Turkey litter amendment at higher rates can inhibit plant production due to soluble salts and NH_4 toxicity*. Coverage results suggest that soluble salts content from the T amendment either delayed or stunted plant growth in the soils. Soil with EC above 2000 μS/cm are a deterrent to plant production. Besides salinity, high NH_4 content and NH_4:NO_3 ratio of the T amendment may induce NH_4 toxicity and impair plant health. Consequently, it is advised to minimize the use of T compost for soil OM enhancement and instead leverage it to improve nutrient content like fertilizers.
2. *Biochar might promote faster initial growth and germination, but it can lead to reduced, eventual diminished plant quality*. Growth curves showed that faster coverage was achieved in 3 out of the 4 soils in the initial stages of growth when biochar was amended. However, the plant N and leaf area measurements showed that the addition of biochar negatively influenced plant morphology and N uptake. Therefore, plant coverage from soil-biochar blends does not represent the overall plant health. To fully capitalize on the benefits of a biochar amendment, it is recommended to enrich wood-based biochar products with complementary fertilizers.
3. *Yard and food waste composts generally lead to higher N uptake and increased leaf area*. In Sanborn and Glenwood soils, N uptake was higher in the BES plants emerging from the T amendment followed by F and then Y. Also, a similar trend was followed for the BES leaf area index in these soils. Greater biomass was accumulated from the Sanborn-Y blends and Clearwater-F blends at higher application rates ($\geq$ 7.5% OM). Between Y and F, the latter contributed to higher uptake of N and leaf area compared to Y. Overall, the best results were achieved with yard waste compost applied at rates 2 and 3. To this end, yard waste and food waste composts are recommended for rapid establishment of roadside vegetation to combat soil erosion. Since overapplication of nutrient-rich compost can cause stormwater quality issues, it is important to incorporate composts at controlled levels (less than 10% by weight) in soil management practices. Future research should include larger-scale experiments to test the incorporation rates of Y and F amendments (at rates 2 and 3) for nutrient losses. Additionally, longer-term trials are needed to observe how organic amendments release nutrients to plants over time.

CRediT authorship contribution statement

Sai Thejaswini Pamuru: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Haluk Sinan Coban:** Writing – review & editing, Methodology. **Oguzhan Saltali:** Writing – review & editing, Methodology. **Angela Farina:** Writing – review & editing, Methodology. **Allen P. Davis:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Ahmet H. Aydilek:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Bora Cetin:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sai Thejaswini Pamuru, Haluk Sinan Coban, Oguzhan Saltali, Angela Farina, Allen P. Davis, Ahmet H. Aydilek, and Bora Cetin report financial support was provided by Minnesota Department of Transportation. Sai Thejaswini Pamuru reports financial support was provided by Compost Research and Education Foundation. Sai Thejaswini Pamuru reports financial support was provided by NSF Research Traineeship (UMD Global STEWARDS) Grant 1828910. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by the Minnesota Department of Transportation (MnDOT) and Local Road Research Road (LRRB), Contract number 1036336 Work Order #1. Sai Thejaswini Pamuru was partially supported by Compost Research & Education Foundation (CREF) and NRT-INFEWS: UMD Global STEWARDS (STEM Training at the Nexus of Energy, WAter Reuse and FooD Systems) that was awarded to the University of Maryland School of Public Health by the National Science Foundation National Research Traineeship Program, Grant number 1828910. The authors would like to acknowledge Dr. Pranava Chaitanya Jayanti for his useful discussions on growth curves and his assistance with MATLAB computations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122316.

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