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Enhancement in soil fertility, early plant growth and nutrition and mycorrhizal colonization by vermicompost application varies with native and exotic tree species

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Abstract

Purpose The impact of vermicompost on tree-soil systems is not yet fully understood. This study aimed to comparatively investigate the effects of chemical fertilizer, compost and vermicompost on soil enzymatic activities, seedling mycorrhizal colonization, growth and nutrition of one exotic tree species (radiata pine, *Pinus radiata* D. Don) and two native tree species (mānuka, *Leptospermum scoparium* and tōtara, *Podocarpus totara*).

Methods A 12-month-long pot trial was set up in the glasshouse with a factorial design of three tree species (radiata pine, tōtara and manuka) by six treatments, including T1-control, T2-chemical fertilizer, T3-HS compost, T4-HS vermicompost, T5-LS vermicompost and T6-CM vermicompost. We assessed the main effects and interactions of treatment and species on soil chemical and biological properties, plant growth and nutritional responses.

Results Compared to the untreated control (T1), application of vermicomposts (T4-T6) and compost (T3) significantly improved soil chemical properties and enzymatic activities, and increased total seedling dry weight by 160–260%, shoot concentrations of nitrogen (N) by 54–97% and phosphorus (P) by 61–91%. Vermicomposts were comparable to diammonium phosphate (DAP) applied at 133 kg N ha^{-1} (T2) in stimulating the growth of native species (mānuka and tōtara) without negative impact on mycorrhizal colonization, with T5 being better than DAP (T2) in promoting mānuka growth. However, application of vermicompost alone was less effective than DAP in stimulating the exotic radiata pine growth. Overall, soil activities of dehydrogenase, urease, acid phosphatase and invertase were significantly and positively correlated to total C and N and exchangeable Ca and Mg.

Conclusion The increased growth of three tree species after application of vermicomposts was mainly related to improved N and P nutrition associated with enhanced root growth and soil enzymatic activities. Our findings imply that the vermicomposting products from septic tank waste could be a promising alternative to inorganic fertilizers in land application or greenhouse potting media of native tree species.

Keywords Vermicomposts · Growth · Nutrition · Tree species · Soil fertility

1 Introduction

Vermicomposting has been proposed as a low-cost technology for rural communities to stabilize sewage sludge for use as a soil amendment. This is because vermicomposting can reduce pathogens and organic contaminants while generating a valuable product rich in plant nutrients (Rodriguez-Canche et al. 2010; Yadav et al. 2010). Vermicomposts have low C:N ratios, high porosity and high water-holding capacity (e.g. Lazcano and Domínguez 2011), are rich in nutrients (e.g. Domínguez 2004) and in humic-like compounds (e.g. Canellas et al. 2002), possess active micro-organisms

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fuelling enzyme activities (Lazcano et al. 2013; Zhao et al. 2020) and can enhance soil fertility through improving soil physicochemical properties (Lazcano and Domínguez 2011; Zhao et al. 2017; Demir 2019), microbial properties (Doan et al. 2013; Lazcano et al. 2013; Zhao et al. 2020) and enzymatic activities (Srivastava et al. 2011; Tejada and Benítez 2011; Usmani et al. 2019). Through their role as organic fertilizers, vermicomposts are therefore increasingly considered in agriculture, forestry and horticulture as a promising alternative to inorganic fertilizers and/or peat in land application or greenhouse potting media. Positive impacts of vermicomposts on seed germination, vegetative growth, plant flowering, fruit yield and quality have been reported mostly for agricultural crop and horticultural plant species (e.g. Domínguez 2004; Lazcano and Domínguez 2011; Zhao et al. 2017; Blouin et al. 2019) partly due to enhanced mycorrhizal colonization (Hameeda et al. 2007; Wathira et al. 2016; Zeighami et al. 2020) and nutrient uptake (Tejada and Benítez 2011; Kumar et al. 2013; Bellitürk et al. 2022). However, fewer data are available on woody forestry species such as acacia, eucalyptus and pine, in particular regarding the early growth of such species (Donald and Visser 1989; Lazcano et al. 2010). This could be critical in case of application of vermicompost to young seedlings in tree nurseries or plantation forests, as the effects of vermicompost on plant-soil systems are not yet fully understood and there is great variability in the magnitude of the effects reported in different studies (Lazcano and Domínguez 2011). Further research is needed to address both the effects of vermicompost on the soil chemical and biological properties and the subsequent growth of important tree species.

In New Zealand, vermicomposting, a mixture of septic tank waste (i.e. sludge) and green waste, is an emerging technology for small local or Maori communities with the objective of recycling the different waste products of the community. The concomitant use of several green waste products along with the septic tank wastes will add value to the resultant vermicomposting product, which may make land application or its use in potting media more publicly acceptable. In previous studies, vermicomposting has been shown to produce a stabilized product and reduce or even eliminate pathogen from the wastes (Eastman et al. 2001; Monroy et al. 2009; Rodríguez-Canché et al. 2010; Schaik et al. 2016). One likely destination for these stabilized products in New Zealand is the forestry sector, which is characterized both by exotic fast-growing tree species and by natural forests composed of a variety of endemic native tree species, of which some can be used for production purposes. So far, it has been reported that vermicompost had contrasting effects on the growth of nursery tree species (Donald and Visser 1989), different genotypes of the same species or different plant functional types (Zaller 2007; Lazcano et al. 2010; Blouin et al. 2019), indicating that the effects of vermicompost might depend greatly not only on the type of vermicompost but also on the species or genotypes studied. Although the exact mechanisms are not known, the previous studies highlight that species and/or genotype-specific responses should be considered when giving recommendations on the optimum proportion of vermicompost amendment to horticultural potting substrate due to their different sensitivity to the vermicompost chemical composition. The outcome of such vermicompost applications on horticultural substrates with seedlings or directly in the forest at plantation, likely also depends on the nutrient requirements of each species and its growth potential under the local site conditions of New Zealand. From this perspective, the comparison of fast-growing production species with less productive native tree species is pertinent.

In this study, we aimed at evaluating the effect of vermicomposts in the tree-soil system and subsequent seedling growth of one fast-growing production species and two slow-growing native tree species in New Zealand. Radiata pine (*Pinus radiata* D. Don) is a fast-growing exotic tree species introduced to New Zealand. Currently, it is the most important plantation species in New Zealand and has been planted over an area of 1.7 million ha. Radiata pine plantations have traditionally been grown on marginal soils and therefore may benefit from land application of vermicompost. Mānuka (*Leptospermum scoparium* J.R et G. Forst.) and tōtara (*Podocarpus totara* G. Benn ex D. Don) are two important native tree species present in natural undisturbed forests or in secondary forest patches. They have been grown on marginal land for conservation or commercial values in New Zealand. Our working hypotheses were (1) vermicomposts would be a successful alternative to mineral fertilizers in the early development stages of the woody tree species, especially the two native species mānuka and tōtara with lower growth rates; and (2) vermicomposts would have different effects on the mycorrhizal colonization in three tree species. In order to test these hypotheses, we grew seedlings of the three species for 1 year in the greenhouse on soil media with or without different types of (vermi-)composts and at harvest determined the effects on the soil and plant performance. The specific objectives were to assess the effects of chemical fertilizer, compost and vermicomposts on (1) the chemical properties and enzymatic activities of the amended soils at tree harvest, and (2) the growth, nutrient concentrations and mycorrhizal colonization of three tree species (radiata pine, mānuka and tōtara) at tree harvest.

2 Materials and methods

2.1 Characteristics of vermicomposts and the soil

Vermicomposts were produced by the earthworm *Eisenia fetida* from different combinations of septic tank waste or

dairy shed solids (mainly cow manure) with horticultural factory wastes (tomato prunings and palm fibre as bulking agents), as described by Schaik et al. (2016). Briefly, 4 different products tested in this study were produced from our previous vermicomposting trial, including (1) a compost from 50% septic tank waste + 40% palm fibre + 10% tomato prunings made without worms (referred to as HS-compost), (2) vermicompost from 50% septic tank waste + 40% palm fibre + 10% tomato prunings + worms (referred to as HS-vermicompost), (3) vermicompost from 30% septic tank waste + 60% palm fibre + 10% tomato prunings + worms (referred to as LS-vermicompost) and (4) vermicompost from 30% cow manure + 60% palm fibre + 10% tomato prunings + worms (referred to as CM-vermicompost). At the end of the vermicomposting process, the resultant products were analysed for chemical properties and tested for the presence of pathogens. The results showed around one third of the total N in the compost and vermicomposts was immediately available for plant uptake within the first year. Pathogen levels were low/negligible in the final products (Table 1). This made these products permitted to be tested in the subsequent glasshouse pot trial on the growth of tree seedlings.

The soil used in this study was collected to a depth of 20 cm from a pine forest skid site at Kaingaroa Forests near Taupō, New Zealand. Skid sites are created for log preparation and transporting during harvesting. Topsoil is typically removed from a skid site and the soil collected for this study was subsoil with very low total C, N and P and Olsen P concentrations as well as very low cation exchange capacity and exchangeable Ca and Mg concentrations (Table 1). This sandy volcanic ash soil with allophane as the dominant clay mineral is classified as pumice soil in the New Zealand soil classification (Vitric Andosol, IUSS/WRB, 2015). Pumice soils form the major soil type around the Taupō region.

2.2 Trial design, establishment and growth conditions

In this study, the rates of the (vermi-)composts applied in the pot trial were based on the levels of total N and plant-available N in each of the products and set equivalent to the mineral fertilizer rate of 133 kg N ha^{-1} directly plant available. This mineral fertilizer application rate was similar to the usual fertilizer prescriptions (150–200 kg N ha^{-1}) for radiata

Table 1 The chemical characteristics of the compost, vermicomposts and the soil used in this study, at the beginning of the trial

	HS-compost[c]	HS-vermi compost[d]	LS-vermi compost[e]	CM-vermi compost[f]	Soil
pH	6.9	6.7	6.2	5.2	6.3
EC[a] (mS cm^{-1})	8.3	9.4	8.6	8.0	
Total C (%)	31.7	33.5	32.8	31.8	0.02
Total N (%)	2.1	2.0	1.7	1.6	0.01
C:N ratio	15.1	16.8	19.3	19.9	2.0
Total P (%)	0.38	0.36	0.35	0.34	0.005
NO_3-N (mg kg^{-1})	756	2471	3647	5657	
NH_4-N (mg kg^{-1})	5.2	19.8	24.1	34.7	
Olsen-P (mg kg^{-1})	1107	1242	942	1268	0.88
Extractable Ca (cmolc kg^{-1})	117	112	96	67	1.0
Extractable Mg (cmolc kg^{-1})	19	18	18	16	0.29
Extractable K (cmolc kg^{-1})	34	30	27	22	1.1
CEC[b] (cmolc kg^{-1})					5.6
E. coli (CFU g^{-1})	11	6.3	12	1.8	
Salmonella (no 25 g^{-1})	ND[g]	ND	ND	ND	

[a]*EC*, electrical conductivity

[b]*CEC*, cation exchange capacity

[c]*HS-compost*, high septic compost (50% septic tank waste + 40% palm fibre + 10% tomato prunings, no worms)

[d]*HS-vermicompost*, high septic vermicompost (50% septic tank waste + 40% palm fibre + 10% tomato prunings + worms)

[e]*LS-vemicompost*, low septic vermicompost (30% septic tank waste + 60% palm fibre + 10% tomato prunings + worms)

[f]*CM-vermicompost*, cow manure vermicompost (30% cow manure + 60% palm fibre + 10% tomato prunings + worms)

[g]*ND*, not detected

pine plantations at this region (Hunter et al. 1985), where some topsoil is typically removed due to tree harvesting during the previous rotation, resulting in low total soil C, N and P (Table 1). Chemical characteristics of the compost and vermicomposts are listed in Table 1. Relative to the soil, all four (vermi-)composts contained together with N, considerable amounts of P, Ca, Mg and K, available for plant growth.

The use of septic tank waste-derived (vermi-)composts implied our experiment should be carried out under secured conditions as septic tank wastes are subjected to biohazard regulations in New Zealand. Therefore, the pot trial was established under controlled conditions in a glasshouse at Rotorua, New Zealand and ran for 12 months. The trial had a factorial design of 3 species (radiata pine, tōtara and mānuka) × 6 soil treatments × 5 replications (i.e. blocks). The 6 soil treatments were:

1. Soil only (referred to as control, T1)
2. Soil and technical grade diammonium phosphate (DAP), applied at 133 kg N and 148 kg P ha^{-1} (referred to as T2)
3. Soil and HS-compost, applied at 133 kg equivalent plant available N ha^{-1} (referred to as T3)
4. Soil and HS-vermicompost, applied at 133 kg equivalent plant available N ha^{-1} (referred to as T4)
5. Soil and LS-vermicompost, applied at 133 kg equivalent plant available N ha^{-1} (referred to as T5)
6. Soil and CM-vermicompost, applied at 133 kg equivalent plant available N ha^{-1} (referred to as T6)

The black polyethylene pots (4 L) used in this trial had drainage holes covered with a piece of geotextile cloth to prevent soil loss. Each of the 90 pots was filled with the equivalent of 2.54 kg sieved (4 mm) dry soil and wet to field capacity after mixing with the chemical fertilizer, compost and vermicompost for different treatments. Each pot was put on a 30 × 30 cm^2 saucer to contain drainage from watering. Uniform and clean-washed plants (c.a. 6-month-old) of radiata pine (28–30 cm in height), propagated as cuttings from a single clone, and seedlings of tōtara (5–7 cm in height) and mānuka (16–20 cm in height) were planted in the pots. Each pot had one plant. White high-density polyethylene plastic granules were applied to the surface of the soil to inhibit algae growth in the pots. The pots were arranged in a split-plot (species as main plot and soil treatment as subplot), randomized block design with five replications (blocks). The soil water content in the pots was maintained at about 80% of field capacity as determined by weighing the pots. Pots were weighed once every week at the start of the trial, increasing to once every other day as the trial progressed. Water loss from evapotranspiration was replenished by adding tap water to the saucers.

2.3 Growth measurement and plant nutrient analysis

The height of all plants was measured from the beginning of the experiment (age 6 months) at monthly intervals for 12 months until the end of the experiment (age 18 months). At harvesting, the height and soil-level stem diameter of all plants were measured, and then plants were individually harvested and divided into shoots and roots. The roots were gently washed to remove soil particles. After washing, a representative sample of fresh fine roots (diameter < 2 mm) was collected from each pot and conditioned in a sample vial with 10% ethanol for further analyses of root length and mycorrhizal infection. To achieve a representative sample of fine roots, 10–15 roots were cut with scissors from the upper, middle and lower part of each root system. Besides this fine root subsample, each plant was cut into three fractions: shoot (stems, branches and foliage), coarse roots (taproot or other roots having a diameter > 2 mm) and fine roots. These samples were weighed after oven-drying at 70 °C until constant weight for shoot, coarse root and fine root dry biomass. The subsamples on which root length and mycorrhizal infection were assessed were subsequently also weighed after oven-drying at 70 °C until constant weight, permitting estimation of the total fine root weight, total root weight and total dry weight (TDW) in each pot.

The shoot and root samples of three species were analysed for N by LECO CNS 2000 Analyser (Leco Corp., St. Joseph, MI, USA) and for P and potassium (K) by Nexion 300 ICP-MS (Perkin Elmer, Waltham, MA, USA) after HNO_3/H_2O_2 digestion. Nutrient utilization efficiency (g^2 TDW mg^{-1} N, P or K) between the species and treatments was compared using the ratios of total dry weights (TDW, g) to concentrations (mg g^{-1} TDW) of N, P or K, following the formula of Siddiqui and Glass (1981).

2.4 Fine root and mycorrhizal infection assessment

The infection rate of ectomycorrhizas (ECM) on radiata pine roots was assessed on fresh roots under a dissecting microscope without staining as mycorrhizal tissues (mantles, short roots with mantle tissue, hyphae and rhizomorphs) were visible without staining. For each of the radiata pine root samples, roots were retrieved from the sample jar and distributed in a Petri dish. Below the Petri dish, a line intersect paper (line distance 1 cm) was displayed, and non-mycorrhizal root length, mycorrhizal root length, number of apices and ECM infection rate were determined using the line intersect method (Brundrett et al. 1996).

For evaluating the infection rate of arbuscular mycorrhizas (AM) on tōtara and both ECM and AM on mānuka, we

used the ink and vinegar method (Vierheilig et al. 1998). Firstly, roots were cleared with 10% KOH by boiling the roots in this solution for 60 to 90 min (depending on the volume) in an Erlenmeyer flask on a heating plate under a fume cupboard. After cooling down, the KOH solution was replaced by tap water and roots were held in this solution for several days at lab temperature. Most of the root material, with the exception of some thicker roots, was then clear. Tap water was then decanted and roots were boiled in a 5% black ink/vinegar solution. Finally, after cooling down, the ink was decanted and a rinsing solution of water with vinegar was inserted into each Erlenmeyer flask to de-stain the roots. This solution was refreshed several times until the solution showed no further coloration of ink by the roots. Root samples were kept in the solution at laboratory temperature for 10 days at the most until processing. Each sample was then evaluated for AM infection under a 100 × magnification using the grid intersection method. A minimum of 50 intersects between the grid lines placed below the Petri dish and the root fragments in this Petri dish were assessed for each sample. Occurrence of ECM tissue (mantle) or AM tissues (arbuscules, intra cellular hyphae or vesicles) was counted and compared to the total number of intersects, expressed as root length (Brundrett et al. 1996).

2.5 Soil chemical and biological property analysis

Two sets of soil samples from each pot were collected and prepared for analysis. The first sets of soil samples were air-dried and ground to pass a 2-mm sieve for chemical analysis. Soil pH was measured at a soil:water ratio of 1:2.5. Soil total carbon (C) and N were determined by dry combustion using a LECO CNS 2000 Analyser. Soil exchangeable calcium (Ca), magnesium (Mg), K, sodium (Na) and cation exchange capacity (CEC) were measured using the ammonium acetate method (Blakemore et al. 1987). Olsen P was determined using FIA colorimetry after sequential extraction to give a measure of plant available soil P.

The second set of soil samples were sieved at 2 mm and then freshly stored at 4 °C until measurements of enzymatic activities within 1 week. The fresh soil samples were incubated with an artificial substrate under optimum conditions to determine soil urease, invertase, dehydrogenase and acid phosphatase activities by different colorimetric methods. The

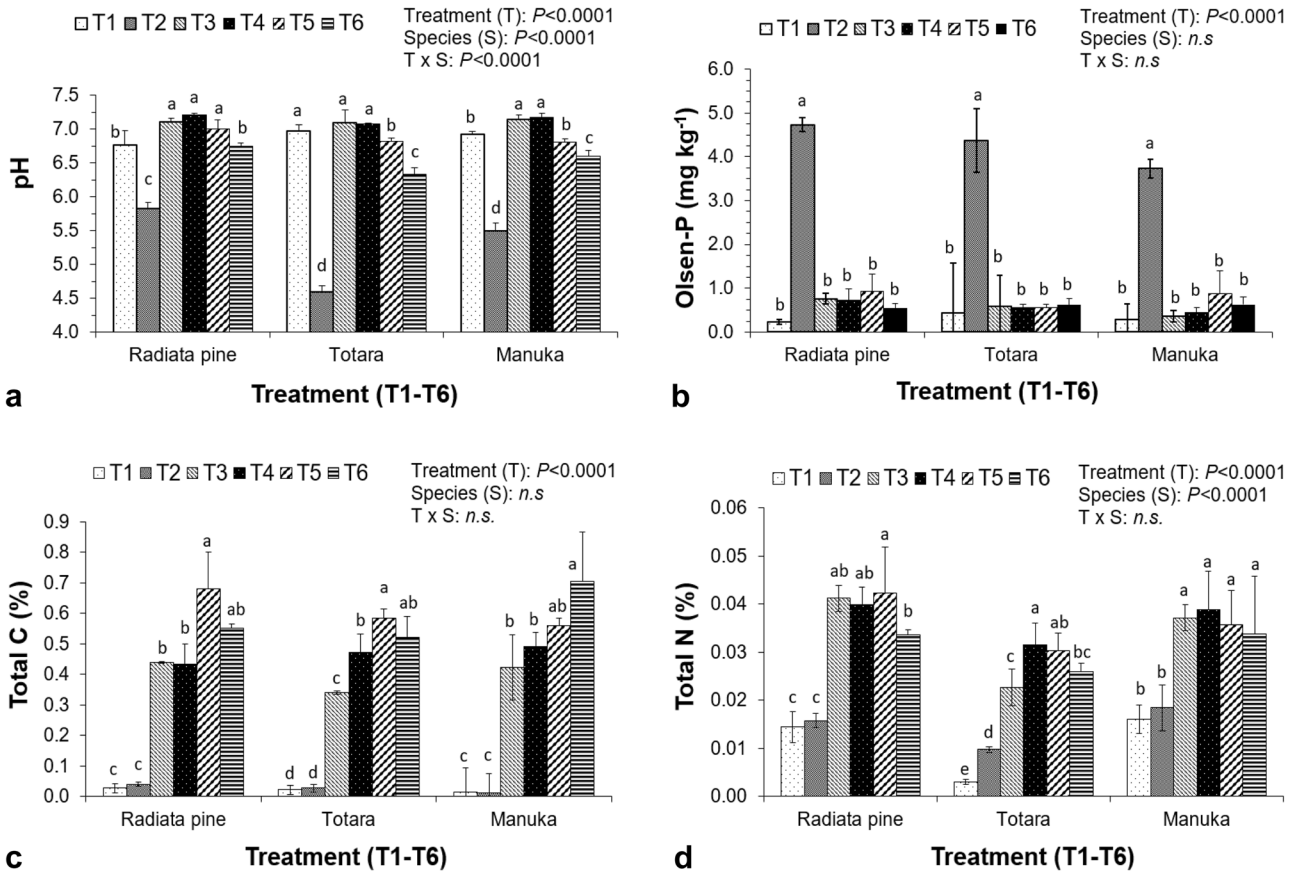

Fig. 1 Effect of soil treatment on soil pH **a**, Olsen-P **b**, total C **c** and total N **d**. Error bars represent ± SD (standard deviation). (Treatment — T1, control (soil only); T2, soil + diammonium phosphate; T3, soil + HS compost; T4, soil + HS vermicompost; T5, soil + LS vermicompost; T6, soil + CM vermicompost)

urease activity was measured by the method of Kandeler and Gerber (1988), the invertase activity was determined by the method of Schinner and Von Mersi (1990), the dehydrogenase activity was measured by using iodonitrotetrazolium chloride (INT) as substrate, according to Von Mersi and Schinner (1991) and the acid phosphomonoesterase activity was determined by the method of Kremer (1994). The enzymes assayed in this study are all involved in important soil processes. Dehydrogenase plays a significant role in the biological oxidation of soil organic matter and is used as an indicator of overall soil microbial activity (Zhang et al. 2010). Urease and acid phosphatase are involved in cycling of N and P, respectively (Caldwell 2005) while invertase mediates the transformation of organic carbon by catalysing the hydrolysis of sucrose to glucose and fructose (Kujur and Kumar Pate 2014).

2.6 Statistical analysis

A two-way mixed model (split-plot design) analysis of variance (ANOVA) was used to determine the statistical significance of species (main plot) and soil treatment (sub-plot) effects and the species by soil treatment interaction on all measured parameters. The soil treatment and species were treated as fixed effects and block was treated as a random effect. When the interaction of species by soil treatment was significant, one-way ANOVA was also applied to test the soil treatment effect for each species separately. Duncan's multiple range test was used at the 95% probability limit ($P < 0.05$) to assess the differences among the treatments. Before analysis of mycorrhizal colonization rate, we transformed the percentage data using an arcsine transformation. Pearson's correlation and multiple regression analyses were carried out across all treatments and species to determine if there were relationships between soil enzyme activities and soil chemical properties. All data were tested for normal distribution and equality of variances and then analysed using appropriate SAS procedures (SAS/STAT Version 9.2).

3 Results

3.1 Effect of soil treatments and species on soil chemical properties

Significant soil treatment effects were found for all measured soil chemical properties, significant species effects were found for soil pH, total N, exchangeable Ca, K and CEC and a significant soil treatment × species interaction was found only for soil pH (Fig. 1). For all three species, soil pH was the highest in soil treatments T3 and T4 and the lowest in T2 (Fig. 1a). The vermicompost from cow manure (T6) resulted in a lower soil pH than in the other vermicompost (T4, T5) and compost (T3) treatments (Fig. 1a). Across all soil treatments, soil pH significantly varied with species, with pH increasing in the order of tōtara (6.5) < mānuka (6.7) < radiata pine (6.9). The lower pH in the tōtara soil was mainly evident in the DAP chemical fertilizer treatment (Fig. 1a), which accounted for the significant species × soil treatment interaction. Compared to the control (T1), only T2 (but not T3–T6) significantly increased soil Olsen-P for all three species (Fig. 1b). The soil Olsen-P in all other soil treatments except T2 was generally low (< 1 mg kg^{-1} dry

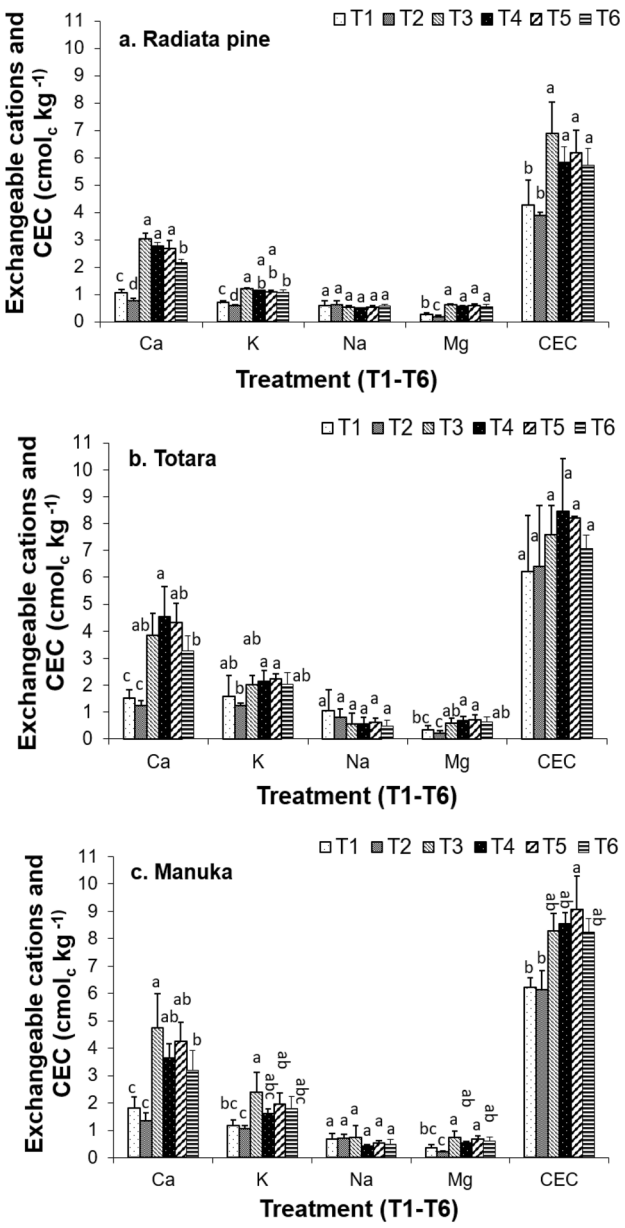

Fig. 2 Effect of soil treatment on exchangeable cations and cation exchange capacity (CEC) in soils with radiata pine **a**, tōtara **b** and manuka **c**. Error bars represent ± SD (standard deviation). For explanation of treatments, see Fig. 1

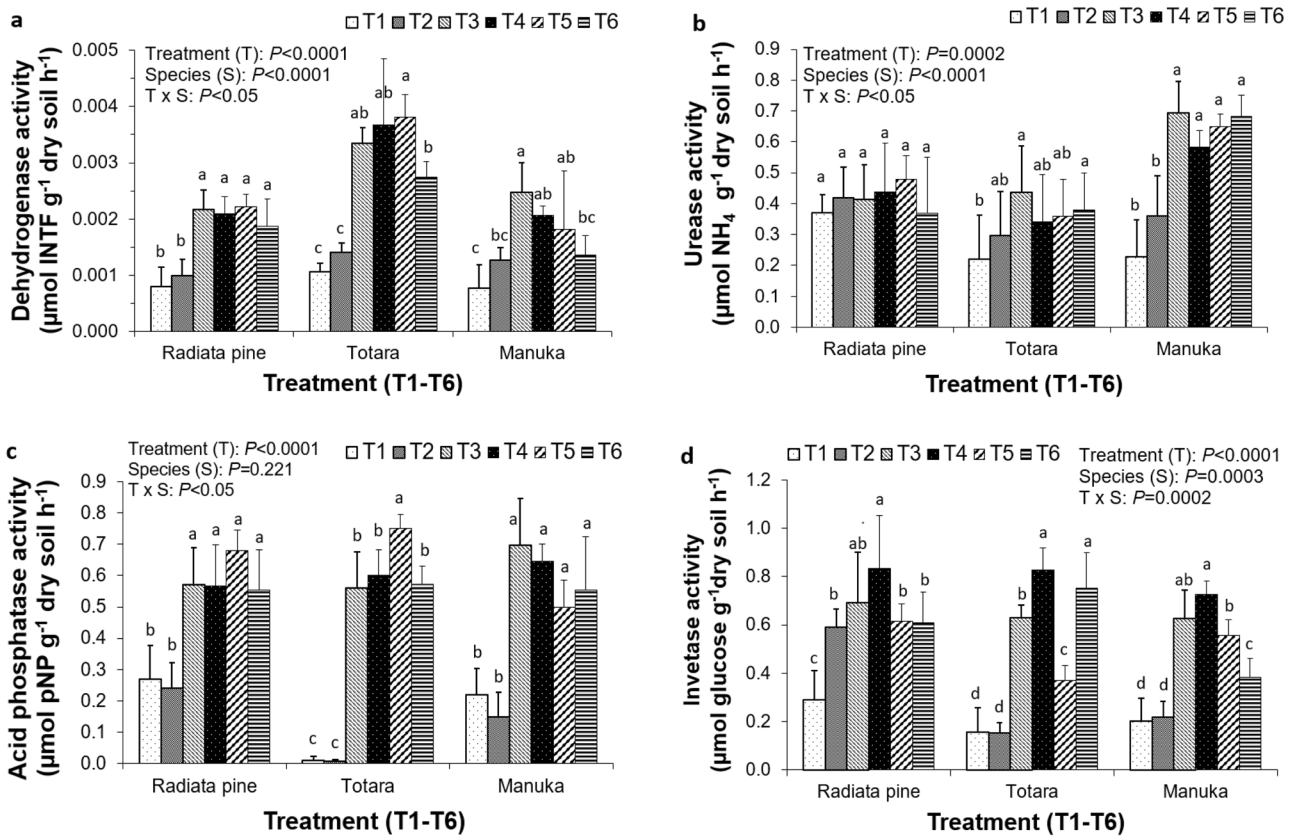

Fig. 3 Effect of soil treatments on activities of **a** dehydrogenase, **b** urease, **c** acid phosphatase and **d** invertase. INTF, IodoNitroTetrazolium violet-Formazan; pNP, para-nitrophenol. Error bars represent ± SD (standard deviation). For explanation of treatments, see Fig. 1

soil), implying a slow release of available P from the compost (T3) and vermicomposts (T4–T6). All soil treatments except T2 significantly increased soil total C by 20–31 fold (Fig. 1c) and total N by 2.8–3.4 fold (Fig. 1d) when compared to the control (T1). Significant species differences were found for soil total N, which was higher ($P < 0.05$) in radiata pine and mānuka soil (0.03%) than tōtara soil (0.02%). Compared to the control, all soil treatments except T2 significantly ($P < 0.05$) increased soil exchangeable Ca (2.0–2.6 fold), Mg (1.8–2.0 fold), K (1.4–1.6 fold) and CEC (1.1–1.3 fold) in all species (Fig. 2). Differences were found among species for soil exchangeable Ca, K and CEC, which were significantly ($P < 0.05$) lower in radiata pine than in mānuka and tōtara.

Table 2 Pearson's correlation coefficients ($n = 54$) between soil enzymatic activities and chemical properties

	Dehydrogenase	Urease	Acid phosphatase	Invertase
pH	0.33^{*}	ns	0.62^{**}	0.53^{***}
Total C (%)	0.53^{***}	0.54^{***}	0.80^{***}	0.62^{***}
Total N (%)	0.44^{***}	0.53^{***}	0.75^{***}	0.71^{***}
C:N ratio	0.56^{***}	0.44^{***}	0.73^{***}	0.52^{***}
Olsen-P (mg kg^{-1})	-0.30^{*}	ns	-0.55^{***}	-0.36^{**}
Exchangeable Ca (cmolc kg^{-1})	0.68^{***}	0.50^{***}	0.74^{***}	0.56^{***}
Exchangeable Mg (cmolc kg^{-1})	0.57^{***}	0.47^{***}	0.74^{***}	0.56^{***}
Exchangeable K (cmolc kg^{-1})	0.58^{***}	0.36^{**}	0.46^{***}	ns
Exchangeable Na (cmolc kg^{-1}	ns	ns	-0.36^{**}	-0.40^{**}
CEC (cmolc kg^{-1})	0.39^{**}	0.40^{**}	0.39^{**}	ns

*, **, *** indicate significance at $P < 0.05$, 0.01 and 0.001 levels, respectively

ns not significant

Table 3 *F* values and probabilities from analysis of variance of soil treatment, species and their interactive effects on dry weights (DW) of shoot, coarse root, fine root, total root and whole plant, and the root/shoot ratio

	DF	Shoot DW	Coarse root DW	Fine root DW	Total root DW	Whole plant DW	Root/shoot
Soil treatment (ST)	5	83.99 $P<0.0001$	17.89 $P<0.0001$	17.83 $P<0.0001$	23.69 $P<0.0001$	61.12 $P<0.0001$	80.97 $P<0.0001$
Species (S)	2	250.27 $P<0.0001$	435.12 $P<0.0001$	363.85 $P<0.0001$	555.34 $P<0.0001$	430.40 $P<0.0001$	78.18 $P<0.0001$
ST × S	10	32.42 $P<0.0001$	14.56 $P<0.0001$	7.51 $P<0.0001$	12.80 $P<0.0001$	24.36 $P<0.0001$	30.84 $P<0.0001$

3.2 Effect of soil treatments and species on soil enzymatic activities

Compost and vermicompost addition increased the activity of all four soil enzymes measured at the end of experiment, which, however, varied with tree species (Fig. 3). Generally, the addition of compost and vermicompost increased the activity of enzymes more in tōtara and mānuka soil than in radiata pine soil. For example, while the addition of compost and vermicomposts increased dehydrogenase activity in the soil of all species, the increase was substantially greater in tōtara soil (Fig. 3a). In contrast to dehydrogenase activity, urease activity was increased substantially more in mānuka soil than in the soil of the other species by the addition of compost and vermicomposts (Fig. 3b). Acid phosphatase activity was very low in tōtara soil in the absence of added organic matter (i.e. T1-T2), but was similar to that in radiata pine and mānuka soil when compost or vermicomposts were added (i.e. T3-T6) (Fig. 3c). Invertase activity was lower in the soil of both native species than in radiata pine soil in the absence of added organic matter, but addition of organic matter generally increased urease activity to similar levels to that in pine soil (Fig. 3d). Mineral fertilizer had no effect on acid phosphatase activity, marginally increased dehydrogenase and urease activity in all species and substantially increased invertase activity in radiata pine soil (Fig. 3). The activities of all four soil enzymes were positively correlated with soil total C and N concentrations, C/N ratio, and exchangeable Ca and Mg concentrations and most enzyme activities were also positively correlated with soil exchangeable K concentrations, CEC and soil pH (Table 2). The activities of dehydrogenase, acid phosphatase and invertase were negatively correlated with Olsen P, while the activities of the latter two enzymes were also negatively correlated with exchangeable Na (Table 2).

3.3 Effect of soil treatments on seedling growth of the three species

Significant effects of species, soil treatment and species × treatment interactions were found for the dry weights of shoots, coarse roots, fine roots, total roots, total biomass and the root/shoot ratio (Table 3). Across all soil treatments, the total dry weight (DW) increments (i.e. DW at harvest minus DW at initial stage) of radiata pine, mānuka and tōtara during the period of the experiment were 24.7, 14.0 and 2.5 g, respectively. Across all species (Fig. 4), the total DW significantly ($P<0.05$) decreased in the following order: T2 > T5, T6 > T4 > T3 > T1 (control). This indicated that the chemical fertilizer (T2) was overall the best in improving seedling growth while vermicomposts from the low content (30%) of septic tank waste (T5) and cow manure (T6) were better than the vermicompost from the high content (50%) of septic tank waste (T4), which were better than the compost

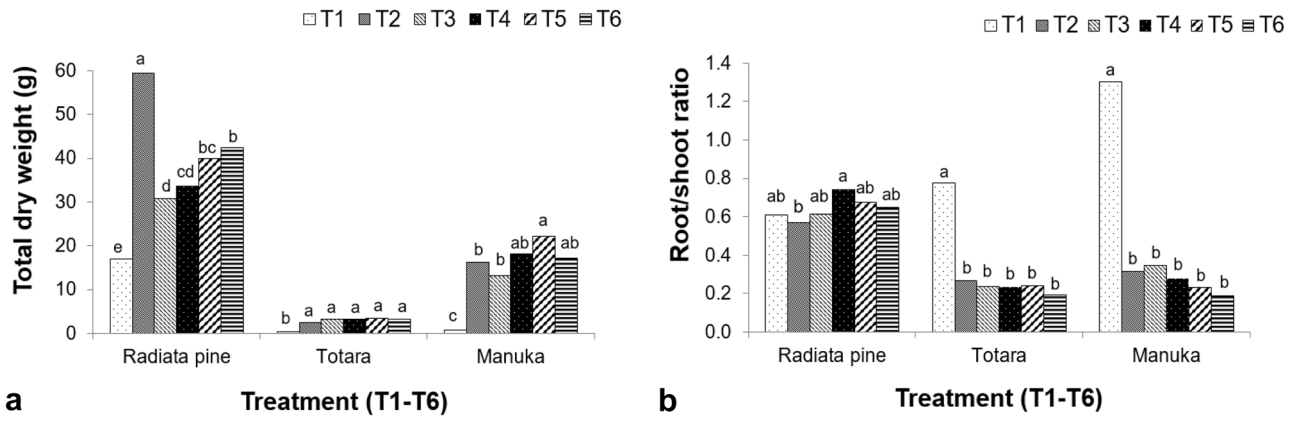

Fig. 4 Effect of soil treatments on total dry weight **a** and the root/shoot ratios **b** of radiata pine, tōtara and mānuka. For each species, soil treatments with different lowercase letters are significantly different at $P<0.05$. For explanation of treatments, see Fig. 1

Table 4 Effect of soil treatments on shoot, coarse root and fine root dry weights (mean ± standard error) of 3 tree species. For each column, values followed by different lowercase letters are significantly different at $P < 0.05$

Soil treat-ment [a]	Radiata pine			Tōtara			Mānuka		
	Shoot (g)	Coarse root (g)	Fine root (g)	Shoot (g)	Coarse root (g)	Fine root (g)	Shoot (g)	Coarse root (g)	Fine root (g)
T1	10.5 d ± 1.0	2.78 c ± 0.71	3.59 c ± 0.81	0.21 b ± 0.09	0.01 c ± 0.01	0.16 b ± 0.04	0.37 d ± 0.12	0.02 b ± 0.04	0.44 b ± 0.04
T2	37.9 a ± 1.1	10.8 a ± 0.75	10.8 a ± 0.85	1.92 a ± 0.28	0.13 b ± 0.02	0.37 a ± 0.04	12.3 bc ± 1.15	0.60 a ± 0.04	3.42 a ± 0.04
T3	19.0 c ± 1.0	5.04 b ± 0.70	6.65 b ± 0.82	2.43 a ± 0.26	0.20 a ± 0.02	0.43 a ± 0.04	9.80 c ± 1.14	0.56 a ± 0.04	2.80 a ± 0.04
T4	19.4 c ± 1.1	5.24 b ± 0.72	9.04 ab ± 0.82	2.71 a ± 0.28	0.18 ab ± 0.02	0.44 a ± 0.04	14.2 b ± 1.20	0.64 a ± 0.04	3.34 a ± 0.04
T5	23.8 b ± 1.2	7.05 b ± 0.82	9.03 ab ± 0.93	2.81 a ± 0.29	0.22 a ± 0.02	0.46 a ± 0.04	17.9 a ± 1.31	0.75 a ± 0.04	3.54 a ± 0.04
T6	25.8 b ± 1.0	6.36 b ± 0.73	10.4 a ± 0.84	2.70 a ± 0.25	0.13 b ± 0.02	0.38 a ± 0.04	14.5 ab ± 1.12	0.57 a ± 0.04	2.15 a ± 0.04

[a]Soil treatment — T1, control (soil only); T2, soil + diammonium phosphate; T3, soil + HS compost; T4, soil + HS vermicompost; T5, soil + LS vermicompost; T6, soil + CM vermicompost

(T3) in improving seedling growth (data not shown). The different soil treatments had contrasting effects on different tree species, causing significant interactions of species by soil treatment (Table 3, Fig. 4). For the fast-growing radiata pine, vermicomposts (T4–T6) and compost (T3) were not as effective as the chemical fertilizer (T2) in improving plant growth measured as total DW (Fig. 4a) or DW of shoot, coarse root and fine root (Table 4). By contrast, vermicomposts (T4–T6) and compost (T3) were at least as effective as the chemical fertilizer of DAP (T2) in improving seedling growth of the slow-growing native species, with T5 being better than T2 in promoting mānuka shoot growth (Fig. 4a and Table 4). The ratios of root to shoot varied among the species and treatments (Table 3, Fig. 4b). Across all treatments, the root/shoot ratio was significantly ($P < 0.05$) greater in radiata pine (0.64) than mānuka (0.44) and tōtara (0.34). Across the three species, a significant difference ($P < 0.05$) in the root/shoot ratio was only found between the control (0.90) and the other soil treatments (0.34–0.42). There was a significant interaction between species and soil treatment (Table 3). There was little effect of soil amendments on the root/shoot ratio of radiata pine, in contrast to tōtara and mānuka where the root/shoot ratios significantly declined ($P < 0.01$) in response to all soil amendments (Fig. 4b).

3.4 Effect of soil treatments on plant N, P and K concentrations of the three species

Significant effects of species, soil treatment and species × treatment interactions were found for all concentrations of N, P and K in shoots and roots except the P concentration in shoots for which the species × treatment interaction was non-significant (Table 5). The interactions were generally due to the greater increases in all nutrient concentrations that occurred in tōtara and mānuka than radiata pine. When compared to the control, the additions of DAP chemical fertilizer, compost and vermicomposts significantly and substantively increased the concentrations of N and P in shoots and roots of all three species (Table 6). A similar pattern occurred with K, with the exception of radiata pine, where DAP addition (i.e. T2) reduced shoot K concentrations. In this study, the differences among soil treatments T2–T6 were generally not significant for N, P or K concentrations in shoots or roots (Table 6). Across all treatments, concentrations of N, P and K in both shoots and roots were always greater in tōtara and mānuka than in radiata pine (see mean in Table 6). Concentrations of these nutrients were negatively ($P < 0.01$) correlated with total dry weights (TDW) of the three tree species. Correlation coefficients between the concentration of N, P or K in shoots and TDW of

Table 5 *F* values and probabilities from analysis of variance of soil treatment, species and their interactive effects on concentrations of N, P and K in shoots and roots

		Shoot			Root		
	DF	*N*	*P*	*K*	*N*	*P*	*K*
Soil treatment (ST)	5	22.50 $P < 0.0001$	11.15 $P < 0.0001$	16.32 $P < 0.0001$	12.90 $P < 0.0001$	24.61 $P < 0.0001$	11.62 $P < 0.0001$
Species (S)	2	77.98 $P < 0.001$	26.20 $P < 0.01$	50.49 $P < 0.001$	14.04 $P < 0.0001$	20.89 $P < 0.01$	28.86 $P < 0.01$
ST × S	10	2.12 $P < 0.05$	1.41 n.s	4.30 $P < 0.001$	4.49 $P < 0.001$	4.16 $P < 0.001$	4.78 $P < 0.001$

n.s. not significant

Table 6 Effect of soil treatment on N, P and K concentrations in shoots and roots of radiata pine, tōtara and mānuka. For each column, values followed by different lowercase letters are significantly different at $P < 0.05$. For means of N, P or K respectively, values followed by different lowercase letters are significantly different between species at $P < 0.05$

Soil treat-ment [a]	Radiata pine			Tōtara			Mānuka		
	N	P (%)	K	N	P (%)	K	N	P (%)	K
	Shoot								
T1	0.39 c	0.08 b	0.69 b	0.59 b	0.21 c	1.03 b	0.53 c	0.10 b	0.94 b
T2	0.59 ab	0.13 a	0.56 c	1.21 a	0.28 b	2.12 a	0.96 a	0.24 a	1.07 ab
T3	0.57 b	0.14 a	0.93 a	1.00 a	0.34 ab	2.52 a	0.69 bc	0.22 a	1.48 a
T4	0.61 ab	0.15 a	0.92 a	1.08 a	0.30 b	2.19 a	0.89 ab	0.19 ab	1.26 ab
T5	0.66 ab	0.13 ab	0.86 a	1.15 a	0.37 a	2.50 a	0.89 ab	0.26 a	1.60 a
T6	0.67 a	0.15 a	0.84 a	1.15 a	0.33 ab	2.54 a	1.07 a	0.25 a	1.48 a
Mean[b]	0.58 c	0.13 c	0.78 c	1.06 a	0.31 a	2.15 a	0.86 b	0.21 b	1.30 b
	Root								
T1	0.41 b	0.12 c	0.78 ab	0.23 c	0.06 c	0.38 c	0.47 c	0.11 b	0.79 c
T2	0.55 a	0.22 a	0.71 b	0.63 b	0.30 ab	1.32 b	0.84 a	0.42 a	1.00 bc
T3	0.60 a	0.17 ab	0.82 ab	0.94 ab	0.25 b	1.51 ab	0.62 b	0.41 a	1.60 ab
T4	0.61 a	0.20 ab	0.96 a	0.92 ab	0.26 b	1.53 ab	0.77 a	0.51 a	1.80 a
T5	0.62 a	0.16 b	0.75 b	1.19 a	0.37 a	2.10 a	0.88 a	0.45 a	1.43 abc
T6	0.65 a	0.18 ab	0.79 ab	0.81 b	0.25 b	1.68 ab	0.87 a	0.43 a	a
Mean[b]	0.57 b	0.18 c	0.82 b	0.74 a	0.25 b	1.41 a	0.74 a	0.38 a	1.41 a

[a]Soil treatment — T1, control (soil only); T2, soil + diammonium phosphate; T3, soil + HS compost; T4, soil + HS vermicompost; T5, soil + LS vermicompost; T6, soil + CM vermicompost

[b]Mean — the mean of N, P or K is calculated across all soil treatments for each species

three species were $r = -0.61, -0.92$ and -0.63, respectively, indicating that the fast-growing radiata pine had greater nutrient use efficiency than tōtara and mānuka, when calculated as TDW in relation to N, P or K concentrations.

3.5 Effect of soil treatments on mycorrhizal colonization of the three species

Significant effects of soil treatment and species were found for colonization of arbuscular mycorrhizas (AM), but not ectomycorrhizas (ECM). Compared to the control, the DAP fertilizer treatment (T2) significantly ($P < 0.05$) reduced colonization of AM in both mānuka and tōtara, but had no significant impact on the colonization of ECM in radiata pine or mānuka (Fig. 5). Application of compost (T3) or vermicomposts (T4–6) had no significant effect on the colonization of either ECM or AM when compared to the control (Fig. 5).

4 Discussion

4.1 Impact on soil chemical properties and enzymatic activities

This study demonstrated that application of chemical fertilizer (DAP) and organic amendments (vermicomposts and compost) had considerably different impact on soil chemical properties and enzymatic activities. Similar to previous studies (Ngo et al. 2011; Wang et al. 2017), the DAP chemical fertilizer significantly increased soil available nutrients such as Olsen-P and reduced pH, while organic amendments significantly increased soil TC and TN and exchangeable K, Mg, Ca and CEC. In consideration of the greater contents of C, N and exchangeable cations in the (vermi-)composts (Table 1), it is not surprising to observe a large increase of these chemical properties in the soils amended with those organic amendments. In contrast, the much higher concentration of plant-available P (i.e. Olsen-P)

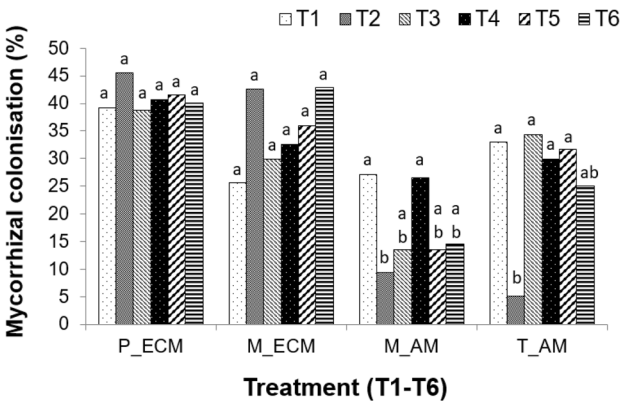

Fig. 5 Effect of soil treatment on root mycorrhizal colonization of 3 tree species (P_ECM, Ectomycorrhizal (ECM) colonization of radiata pine; M_ECM, ECM colonization of mānuka; M_AM, arbuscular mycorrhizal (AM) colonization of mānuka; T_AM, AM colonization of tōtara). For each type of colonization, bars followed by different letters are significantly different (between soil treatments) at $P < 0.05$. For explanation of soil treatments, see Fig. 1

in the soils treated with DAP than the four organic amendments could be attributed to the high content of P contained in this chemical fertilizer. A large reduction of soil pH in the DAP treatment compared to the control and all four organic amendments could be resulted from the greater nitrification of the readily available ammonium nitrogen from this chemical fertilizer, with the release of H^+ ions into the soil. It is well recognized that application of chemical fertilizers causes greater soil acidification (Marschner 2012). Among the four organic products tested in this study, the vermicompost from cow manure had the lowest pH before its use in the pot trial (Table 1), which may explain the lower soil pH in this treatment (T6) by the end of the trial when compared to the two other vermicompost (T4, T5) and compost (T3) treatments. In this study, the addition of compost and vermicomposts considerably increased the activity of all measured enzymes while chemical fertilizer application yielded results not significantly different from the values of the control soils. Our findings support the observations from previous studies (Dinesh et al. 2012; Tejada and Benítez 2011; Xue and Huang 2013). Positive correlations between soil enzyme activities and soil pH, organic matter and total C and N have been reported previously (Nayak et al. 2007; Kujur and Kumar Patel 2014). Higher organic matter levels can provide enough substrate to support higher microbial biomass, and hence higher enzyme production (Nayak et al. 2007). The negative correlations between Olsen P and the activities of dehydrogenase, acid phosphatase and invertase indicate that high soil available P could slow down the functions of these enzymes possible through feedback regulation.

Our study also demonstrated that growing different tree species had different impact on soil chemical and biological properties. Despite no direct evidence from this study, we assume based on previous studies that the differences between species in root activity including nutrient uptake and exudation of organic acids might contribute to the observed pH differences. The lower pH in the tōtara soil was particularly evident in the DAP chemical fertilizer treatment, leading to an overall significant species × soil treatment interaction. It has been reported that different soil acidification was caused by different uptake patterns of N source (NH_4^+-N vs NO_3^--N) in Scots pine (Arnold 1992) and Douglas-fir (Gijsman 1990). The lower exchangeable Ca, K and CEC in the soils grown with radiata pine than with mānuka and tōtara could be attributed to the greater uptake of these nutrients associated with greater biomass and growth rate of radiata pine (Fig. 4a). Here, we suppose that the stronger growth effects of radiata pine (than other two species) on exploitation of mineral nutrients from soil organic matter might accelerate the breakdown of compost and vermicomposts in soils and thus lower the soil CEC values. One striking species effect on the soil chemistry occurred in the pots grown with tōtara. Total N levels in the soils of the pots with these tree species were significantly lower than in the soils grown with the other two tree species (Fig. 1d). Based on plant dry weights (Table 4) and plant nutrient concentrations (Table 6) of the 3 species, it seems unlikely that a higher absorption of N from the soil by tōtara seedlings would explain this lower total N level in the soil. On the contrary, tōtara immobilized less total N from the soil than the other species. One may speculate on what happened with the N in the pots grown with this species, either lost through leaching and/or volatilization. The soil dehydrogenase activity in the pots grown with tōtara was overall higher than other tree species, most strongly so for the four organic amendments (Fig. 3a). This would imply a high overall microbial activity and presumably high N fluxes as a result of such high overall microbial activity, which is in support of potential leaching losses in consideration of much smaller root system of tōtara that was unable to incorporate the higher levels of plant available N. Differences in intensity of the different steps of the nitrogen cycle may also explain these species specific differences in remaining total N. However, the urease activity in our study did not show very clearly that the nitrification would be larger in case of tōtara.

4.2 Impact on mycorrhizal colonization, nutrient uptake and growth of exotic and native tree species

In this study, the DAP fertilizer had a negative impact on colonization of arbuscular mycorrhizas (AM) in both mānuka and tōtara, but not ectomycorrhizas (ECM) in radiata pine or mānuka (Fig. 5). Our results partially agree with those of previous studies, which have showed that both AM and ECM abundance and fungal species richness decrease under N fertilization, atmospheric N deposition and P fertilization (Treseder 2004). However, how mycorrhizal root colonization responds to N fertilization or deposition depends on the type of mycorrhizas and background levels of soil N and P (Mohan et al. 2014). For example, they reported that nitrogen fertilization reduced AM abundance and mycorrhizal species richness in P-rich sites and increased AM abundance and species richness in P-limited sites in perennial grassland ecosystems. Application of compost (T3) and vermicomposts (T4–6) had no significant effect on the colonization of either ECM or AM when compared to the control (Fig. 5). However, a positive effect of compost or vermicompost on mycorrhizal colonization has been observed in previous studies (e.g. Hameeda et al. 2007). The disagreement between our findings and the previous observations could be related to the different characteristics of composts and vermicomposts. We suspect that ECM infection did not respond to the treatments in this study either because (a) infection rate of the seedlings in the nursery was rather high everywhere and this was species specific for the tree species

investigated and (b) mycorrhizal infection was uncontrolled, i.e. no inoculum was added to the experiment. Our measurements may thus, relative to field conditions, be based on an incomplete set of ECM fungal species. Therefore, a further study regarding the impact of application of vermicomposts on mycorrhizal colonization under field conditions is warranted.

Concentrations of N and P in the shoots of the control radiata pine plants were at deficient or marginal levels while K was at a sufficient level according to Will (1985). The improved N and P nutrition of radiata pine should therefore directly contribute to the enhanced seedling growth of this species. Although critical nutrient concentration ranges for tōtara and mānuka are not available, the higher N and P acquisition likely contributed to the enhanced growth of these two native species. Improved plant nutrition and growth after application of vermicomposts have been reported for many different plant species (Kumar et al. 2013; Singh and Wasnik 2013). This study demonstrated that the fast-growing radiata pine had greater nutrient use efficiency (calculated as TDW in relation to N, P or K concentrations) than tōtara and mānuka. This finding agrees with that of Siddiqi and Glass (1981). It has been well documented that fast-growing species have greater nutrient use efficiency than slow growing species (Poorter et al. 1990). In this study, the differences among soil treatments T2–T6 were generally not significant for N, P or K concentrations in shoots or roots. The better growth of radiata pine and mānuka in T4–6 (vermicomposts) than T3 (compost) (Fig. 4a and Table 4) could be related to the non-nutritional growth stimulation by vermicomposts, possibly due to the formation of plant growth promoting substances (Canellas et al. 2002). However, this needs to be further tested in the future.

Positive effects of vermicomposts on plant growth have been observed in a wide range of plant species (e.g. Fernandez-Luqueno et al. 2010; Lazcano and Domínguez 2011) including forestry species such as *Acacia*, *Eucalyptus* and *Pinus* (Donald and Visser 1989; Lazcano et al. 2010). Vermicompost can stimulate vegetative growth and shoot and root development (Lazcano and Domínguez 2011). In agreement with previous studies, this study also demonstrated the overall beneficial effect of vermicomposts on the shoot and root growth of three tree species. More interestingly, our study revealed the contrasting plant growth responses of exotic and native tree species to various soil amendments. For radiata pine, a fast-growing exotic species, vermicomposts (T4–T6) or composts (T3) were not as effective as the chemical fertilizer (T2) in improving plant growth (Fig. 4a and Table 4). This implies application of these organic amendments might not provide sufficient available N and P (or other nutrients including K, Mg) to meet the nutrient requirement of this fast-growing species because most nutrients in vermicomposts and compost are released gradually through mineralization of the organic matter (Chaoui et al. 2003). So the combined application of mineral fertilizer and organic amendments may be required to provide balanced supply of readily available and slow-release nutrients for better tree growth of this species. It has been reported that application of a combination of mineral fertilizer and vermicompost in the field can support better plant growth of *Allium cepa* L., when compared to the application of mineral fertilizer or vermicompost alone (Srivastava et al. 2012). By contrast, vermicomposts (T4–T6) and compost (T3) were at least as effective as the chemical fertilizer of DAP (T2) in improving seedling growth of the slow-growing native species, with T5 being better than T2 in promoting mānuka shoot growth (Fig. 4a and Table 4). These findings are in support of our working hypothesis 2 that the vermicomposts would be more effective for the two native species of mānuka and tōtara with lower growth rates. Our results also agree with the previous studies, which have demonstrated that vermicomposts have different effects on the growth of different nursery tree species (Donald and Visser 1989), six different progenies of maritime pine (Lazcano et al. 2010) and three different tomato varieties (Zaller 2007). The much greater overall root/shoot ratio in the control (0.90) than other soil treatments (0.34–0.42) could be resulted from the acclimation responses of these tree species, especially tōtara and mānuka, to low nutrient availability in the soil. It has been reported that root growth is favoured when N, P or sulphur (S) are limiting (Ericsson, 1995). Changes in root architecture can mediate the adaptation of plants to soils in which nutrient availability is limited by increasing biomass allocation to roots or the total absorptive surface of the root system (e.g. López-Bucio et al. 2003).

Overall, under our conditions of nutrient-poor soils, application of compost or vermicompost enabled effectively to improve soil fertility and increase available nutrients and therefore plant growth. Vermicompost does appear to be a relevant alternative to chemical fertilizers because it leads to similar enhancements in plant growth of tree species, especially slow-growing native species. This is generally in support of our working hypothesis 1 that vermicomposts can be a successful alternative to mineral fertilizers in the early stages of development of the woody tree species. Our results confirm those of Chaoui et al. (2003), who reported that both vermicompost and compost amendments significantly increased the total amount and availability of soil N, P and K, and wheat P and K uptake and growth. The use of organic amendments (such as vermicompost) has been found effective for improving soil structure and fertility, increasing soil microbial diversity, populations and enzymes, improving soil moisture-holding capacity, increasing cation-exchange capacity (CEC), and finally also crop yields (Lazcano and Domínguez 2011; Tejada and Benítez 2011).

5 Conclusions

Application of vermicomposts and compost significantly improved soil enzymatic activities and nutrient availability, seedling nutrition and growth of both native and exotic tree species. Vermicompost application improved the seedling growth of two slow-growing native species more than chemical fertilizer and vermicomposts did not have a negative effect on AM colonization. The results from this study are important for Maori communities wishing to sustainably manage their wastes and improve the growth of native plant species in marginal land by application of vermicomposts, or increase seedling growth by using vermicompost as an alternative to chemical fertilizers in forest nurseries.

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Declarations

Human and animal rights and inform consent This study does not involve human participants and/or animals. This manuscript is original, and it has not been previously published or submitted in part or whole. No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. All authors have agreed to be listed and approved the submission to Journal of Soils and Sediments.

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