

# Decomposition of Fine Roots and Aboveground Agroforestry Litter as Plant-soil Feedback After Volcanic Ash Deposition

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## Research Article

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# Abstract

## Background and Purpose

Above- and belowground organic inputs feed decomposer communities in the soil enhancing soil organic matter ( $C_{org}$ ) formation, depending on the vegetation, soil, contextual factors and human management of (agro)ecosystems. Plant-soil feedback in volcanic ash rapidly increases  $C_{org}$  during transformation to Andisols. We quantified fine root turnover in agroforestry systems, including the ash-adapted native tree *Parasponia rigida*, as part of the C accumulation process.

## Methods

Fine root (<2 mm) decomposition was quantified with a total of 1440 litterbag samples, testing the effects of six tree species (*Coffea canephora*, *Persea americana*, *Durio zibethinus*, *Gliricidia sepium*, *Falcataria moluccana* and *Parasponia rigida*), three distances to the nearest coffee trees, two seasons (rainy and dry), two sites (with and without recent ash deposits), four time intervals (2, 4, 6 and 8 weeks) and five replicates. Soil temperature around the litterbags was used to derive equivalent decomposition rates at 20°C. The ratio of lignin plus phenolics over nitrogen was used as main litter quality indicator.

## Results

Decomposition of fine tree roots was up to three times faster than that of aboveground litter with the same quality index measured in the same habitat. Root decomposition was slower in topsoils with recent volcanic ash, with a mean residence time extended by, on average, two weeks. Decomposition of roots of the ash-adapted native tree *Parasponia rigida* was especially rapid.

## Conclusions

Fine root turnover contributes to the  $C_{org}$  accumulation that turns low-C volcanic ash into high-carbon andic soil and has relatively short necromass residence times.

# Introduction

Plant-soil feedback involves a two-way influence. Beyond the role of soil as a physical substrate for plant growth and mediator of water and nutrient supply, it forms the habitat for soil biota that have a wide spectrum of relationships with plants, ranging from rhizovores, symbionts, pathogenic invaders and rhizosphere biota to soil engineers that modify the soil (Brussaard 1998; van Noordwijk et al. 1998; Bergmann et al. 2020). Plants, in reverse, influence soil via the soil biota, but also through their influence on soil organic matter, aeration, soil structure, (re)distribution of soil water and changes in rhizosphere conditions for subsequent plants (Rovira 1959; van Noordwijk et al. 1991; Burgess et al. 1998; Meng et al. 2020). Agroforestry as land use that combines perennial and annual plants has been specifically appreciated for its positive feedback on soil conditions (Bayala et al. 2015; Cardinael et al. 2020). An environment where the two-way relationship between plants and soil is particularly rapid and relevant is in the transformation of freshly deposited volcanic ash to an Andisol (or at least a soil with andic properties) (Nanzyo 2005; Fiantis et al. 2019).

Volcanic soils have significantly greater N content, higher pH and lower C:N than non-volcanic soils (Sanchez 2019; Yokobe et al. 2021). Yet, volcanic ash enters the soil system at very low organic matter concentrations (<0.3%). The substrate can rapidly increase in  $C_{org}$  as sorption sites abound, as long as the soil biological carbon cycle is active. Volcanic soils contain an allophane compound, Imogolite, a nanotubular aluminosilicate mineral that can exert a control on carbon dynamics (Fernandez-Martinez et al. 2020). The ash may obtain andic properties when turning into Andisols, associated with a  $C_{org}$  concentration of up to 10% (Minasny et al. 2021). Nutrients such as cations and phosphorus from volcanic ash deposits will become available to plants over time after chemical and physical weathering (Lansing et al. 2001). The source of the increased soil C content after volcanic ash deposition can be above- and belowground parts of the vegetation. In any soil, organic matter derives mostly from plants, either through aboveground litterfall or belowground turnover of roots (Lal 2004).

The relative importance of these two pathways for plant-soil feedback may well depend on the vegetation, soil conditions and soil management. Vegetation influences the seasonal pattern of litterfall, the presence of decomposition-inhibiting polyphenolics and lignin, the degree of internal nutrient recycling before litterfall, and the resulting ratio of carbon to nitrogen. Relevant soil conditions may vary with climatic zones (Guerra et al. 2020). It includes the effect of soil biota on access by microbes through the diminution of coarse organic matter. Soil pH effects the balance between fungal, microbial decomposers and bioturbation that moves surface litter into the soil matrix. Soil management matters, especially through the degree to which crop residues gets worked into the soil, fertilization, and direct effects on soil biota. In a direct comparison of foliar and fine-root litter, microbial alteration of fine root litter appeared to favor greater initial stabilization of microbially derived C and N in Soil Organic Matter (SOM) fractions with long mean turnover times, such as humin, compared to needles with a faster decay rate (Mambelli et al. 2011).

It is unclear to what extent the increase in  $C_{org}$  after ash depositions derives from below or aboveground plant sources. Ash deposition events on vegetation often induce litterfall, causing a mixture of ash and aboveground litter to cover the soil surface. As a consequence of mortality or de-leafing of the vegetation, ash deposition can also induce, enhance turnover of fine roots, as a source of soil organic matter. Measurements of decomposition rates of above- and belowground litter in the presence or absence of volcanic ash can contribute to the process-level understanding of the transformations volcanic ash deposits undergo as part of the recovery of vegetation. In post-volcanic eruption conditions, volcanic ash input can strongly affect fungal, bacterial biomass and community structure of soil organisms in the litter layer in a study in Argentina (Berenstecher et al. 2017). Under standard test conditions ash addition induced a fourfold increase in the decomposition rate of native litter sources; under field conditions, however, the lower water content in ash layers, due to poor rewetting, could lead to a net decrease of decomposition rates (Piazza et al. 2018).

Root decomposition may differ from that of aboveground organic inputs through its inherent quality characteristics such as lignin, polyphenolics and C:N ratio (Tong et al. 2012; Guerrero-Ramírez et al. 2016). Location in the soil relative to aggregates and macropores, influencing aeration and access by comminutors and microbial decomposers, however, may cause different responses (Zhang et al. 2005), for example because the location allows access by decomposers of mineral N from the surrounding matrix. The relative contribution of above- and belowground necromass inputs to the soil can differ from the above- to belowground biomass ratio (with a global average of 4:1, but lower ratios in less-favorable environments; Cairns et al. 1997; Finér et al. 2011; van Noordwijk et al. 2015), if the half-life time of leaves (as biomass) differs from that of fine roots (as biomass), and/or when the ratio of fine-to-structural roots differs from that of woody-stem-and branches to leaves. If fine

roots turnover once per year, they may represent 33% of global annual net primary productivity (Jackson et al. 1997). The estimated fine root input in a global review of forest studies accounted for 41% of the annual litter input (Freschet et al. 2013). According to this review, fine roots and stems had, on average, a 40% slower decomposition rate than leaves, but higher than that of fine stems of the same species. The half-life time of fine roots (as biomass) characterizes the ratio of standing root biomass and annual root necromass inputs to the soil. Estimates of the half-life time for fine roots of trees vary from two months in tropical agroforestry conditions (van Noordwijk et al. 2004) it may be influenced by climate variability and climate change (van Noordwijk et al. 1998). Coarse roots (>2 mm) are important for belowground biomass C storage (Palviainen and Finér 2015), but may play a lower role in contributing to soil C. Around 49% of the total biomass in coffee agroforestry systems was in coffee tree root biomass, probably due to the frequent pruning of coffee branches (Defrenet et al. 2016).

Volcanic ash from the eruption of Mount Kelud changes the physical, chemical, and biological properties of the soil (Ishaq et al. 2020a). The  $C_{org}$  content in the Kelud volcanic ash was very low, around 0.35%, with an acidic pH of around 4.33 and a low cation exchange capacity (Utami et al. 2017). One of the changes that occur after ash deposition is the compaction of the soil surface, decreasing infiltration rates. After mixing with water, oxides ( $SiO_2$  and  $Al_2O_3$ ) in volcanic ash can induce a cementation and hardening process, reducing soil porosity and permeability (Mueller et al. 2017). Close to the volcano, a specialized ash-adapted tree species with  $N_2$  fixing abilities, *Parasponia rigida*, is the first to recover after an eruption and contribute organic matter from the above and belowground litter inputs (Ishaq et al. 2020b). On cropped lands, farmers hoe the soil surface after volcanic ash deposition and add organic matter from leaves and twigs left over from harvest (organic matter) found around their land as well as manure. The addition of organic matter in the form of *Tithonia* and *Leucaena* leaf litter on agricultural land affected by the eruption of Mount Kelud, increased pH, cation exchange capacity,  $C_{org}$  content, total N, and neutralized toxic Al ions (Utami et al. 2017). The recovery of soil conditions without external organic inputs and its dependence on tree root turnover has yet to be quantified for the specific conditions of Mount Kelud and its vegetation.

The purpose of this study was to evaluate 1) the rate of decomposition of fine roots of local plants and their relationship to litter quality metrics, 2) the effect of additional volcanic ash deposition on the soil on the rate of decomposition below the soil surface, 3) the relative importance of environmental factors in litter decomposition rates for specifically ash-adapted and common agroforestry tree species.

## Materials And Methods

### *Location and time*

This research was conducted in coffee-based simple agroforestry owned by farmers in two different sites around Mount Kelud (Figure 1). The first location was Tulungrejo Village, Ngantang District, Malang Regency ( $112^{\circ} 21'49''$  -  $112^{\circ} 22'286''$  E,  $7^{\circ} 49'45''$  -  $7^{\circ} 56'03''$  S), which was affected by the recent eruption of Mount Kelud in February 2014. The second location was in the adjacent Krisik Village, Gandusari District, Blitar Regency ( $152^{\circ} 30'152''$  -  $152^{\circ} 39'7''$  E,  $7^{\circ} 66''$  -  $8^{\circ} 98''$  S), which was not affected by the eruption.

Annual rainfall in Ngantang district ranges from 2900-4400 mm, with 4 dry months (mean rainfall <200 mm), with an average temperature of 24°C. Eight months per year are wet (rainfall > 200 mm) with an average rainfall of 316 mm/month, and an average air temperature of 28°C. According to existing data for 2012-2019 (Figure 2), rainfall

in the Gandusari District followed the same seasonal pattern but had lower total rainfall during the rainy season than in Ngantang.

The experiment was carried out five years after the ash deposition, in two seasons: in the rainy season (December 2018 to February 2019), and the dry season (July to September 2019). We conducted the experiment in simple coffee (*Coffea canephora*)-based agroforestry system because this land use is the most affected by Kelud eruptions. In this location, coffee was planted with shade trees such as gliricidia (*Gliricidia sepium*), fast-growing timber trees including sengon (*Falcataria moluccana*, also known as *Paraserianthes falcataria*) and *Parasponia rigida*, and fruit trees including durian (*Durio zibethinus*), and avocado (*Persea americana*).

#### *Vegetation, soil and litter analysis*

The vegetation of the research area was characterized through sample plots of 20×20 m<sup>2</sup> for trees with a diameter (1.3 m above the ground) of 5-30 cm. For a bigger tree with a diameter > 30 cm, we enlarged the plots to 20×100 m<sup>2</sup>. Tree girth was measured, converted to diameter, and aggregated to obtain the tree basal area (BA, m<sup>2</sup> ha<sup>-1</sup>). Plots were categorized as 'simple agroforestry' (Hairiah et al. 2006) if the basal area of the dominant tree species is <80% of the total (differentiate it from 'monoculture'), with less than five tree species (differentiate it from 'complex agroforestry').

Soil samples were collected of the topsoil (0-15 cm depth) by bulking five subsamples per plot in the area subsequently used for litter bag placement. An iron box (20 x 20 x 10 cm<sup>3</sup>) was used for determining the bulk density of the 0-10 cm layer and drying at 105<sup>0</sup>C. Bulked soil samples were analyzed in the laboratory for pH (both in H<sub>2</sub>O and 1N KCl, in a 1:5 soil: solvent mixture, after 1 hour equilibration), C<sub>org</sub> (Walkley and Black 1934; using potassium dichromate, K<sub>2</sub>CrO<sub>7</sub>), and soil texture (sand, silt and clay fractions using pipette methods).

#### *Litterbags*

Loss of dry weight (further described as 'decomposition') of fine roots (< 2 mm diameter) was assessed in a factorial design with four factors: (a) tree species (6 variations: coffee (*C. canephora*), avocado (*Persea americana*), durian (*D. zibethinus*), gliricidia (*G. sepium*), sengon (*F. moluccana*), and parasponia (*Parasponia rigida*)), (b) distance to the nearest coffee tree (3 variations: 0.5 m, 1 m, and 1.5 m), (c) seasons (rainy and dry), (d) Volcanic ash addition (with and without volcanic ash addition) as 'blocks' in the two sites described. Each treatment was replicated five times, and was observed at 2, 4, 6, and 8 weeks after the start of the experiment. A total of 1440 litterbag samples was used.

To obtain approximately 0.5 kg of fine root samples as material for the litterbag experiments, fine roots of five tree species common in the local agroforestry systems were sampled from the +Ash site (tree age more than 5 years). Meanwhile, the parasponia roots were sampled higher up on Mount Kelud where the species dominates the vegetation (Ishaq et al. 2020b). Root sampling was done by tracing the main root from the base of the stem, following secondary branch roots, and collecting soil-root samples that were washed with roots with a diameter of <2 mm retained. The obtained root samples were cut to 5 cm pieces, washed and air-dried. Subsamples were weighed, dried in an oven at 80<sup>0</sup>C for 48 hours, and re-weighed to obtain the moisture content. A similar procedure was repeated for the second season. The samples of oven-dried roots from the first season (rainy) of the experiment were stored and mixed on an equal-weight basis with those of the second season for analysis of total N (Kjeldahl method), lignin (Goering and Van Soest 1970), and polyphenols (Anderson and Ingram 1989).

Samples of roots from each tree were weighed to a standard of 2 g equivalent of oven-dried weight. We then put the samples into a 5 cm x 10 cm of fine nylon bag (mesh size <1 mm, normally used in tea infusion bags) and buried into the soil at a depth of 10 cm, at the specified distance (0.5 m, 1.0 m and 1.5 m) from a coffee tree, according to the time group observed. The sample of roots in a nylon bag was inserted into an augered hole, covered with soil and pressed so that there was good contact between the soil particles and the nylon bag. A labelled rope remained visible at the soil surface. During the experiment, soil and air temperature in all plots were recorded every 30 minutes with a HOBO sensor and data logger.

At the indicated observation time, we retrieved the litter bags and removed the roots from the nylon bag by floating in the water to ensure that no roots were lost. The roots were then rinsed in water, inserted in a labelled paper envelope, dried in an oven at 80°C until the weight was constant (48 hours), and weighed.

### *Data analysis*

The root decomposition rate constant based on an exponential decay equation for remaining dry weight (Olson, 1983):

$$X_t / X_0 = e^{-kt} \dots \dots \dots [1]$$

where:

$X_t$  : mass remaining at time t [g]

$X_0$  : initial mass [g]

t : time [week]

k : decomposition rate [week<sup>-1</sup>]

As sample handling might have influenced the root dry weight retrieved, the sample taken after two weeks in the field was used as an 'initial' sample in a regression of the logarithm of remaining dry weight against time (2,4,6 weeks) of incubation. The replicate samples for the same time and treatment combination were averaged for the regression analysis. The standard error estimate of the regression analysis was used to evaluate differences in estimated k values between treatments. The mean residence time (MRT) was derived as 1/k and the half-life time (t<sub>50</sub>) as -Ln(0.5)/k or 0.7/k (Hairiah et al. 2006). A temperature correction to derive an equivalent k value at 20°C was applied based on temperature X:

$$k_{20} = k_X / Q_{10}^{((X - 20)/10)} [2]$$

where  $Q_{10}$ : the relative increase in a biological rate constant for a 10°C increase in temperature (at least below 30°C, (Kätterer et al. 1998) was estimated to be 2.2 (Delogu et al. 2017).

In an analysis of variance on the remaining dry weight at the end of the experiment, the experiment was considered as a randomized block design with three factors factorially tested in location-based blocks.

The relationships between k values and half-life time of different litter sources and the quality of organic matter sources, and between the sites (with and without ash) to the soil temperature were assessed by regression

analysis. The relationships were accepted at  $P < 5\%$ . To assess the effect of additional volcanic ash deposition on the soil on decomposition rate of above and below the soil surface, we compared our data with above-ground litter study conducted by Ishaq et al. (2020a) which was conducted in the same research location. We performed analysis of variance to confirm the statistically significant between the factors (season, location, and root tree). All statistical analysis was performed using Genstat Software Edition 20.

## Results

### *Site characterization*

The total tree count in the +Ash site was higher, with a lower tree basal area than the -Ash site. On average, 56% of trees in the +Ash site had a stem diameter of 5-10 cm, 34% of trees one of 10-30 cm and 10% a diameter of >30 cm (Ishaq et al. 2020a), while in the - Ash site was 25%, 75% and 0, respectively. Beyond coffee, the tree species at the + Ash site consisted of 77% fruit trees, 2% timber trees, and 21% non-timber shade trees; while the types of trees in the -Ash location were 52% fruit trees, 45% timber trees, and 3% non-timber shade trees.

Five years after the ash deposition, topsoil on the +Ash sites still had a lower  $C_{Org}$  content (1.69%) than that at the -Ash location (2.12%; Table 2).

Soil temperature at 15 cm depth in the + Ash location ranged from 19.26 to 26.20<sup>0</sup>C, while air temperature ranged from 17.02 to 35.74<sup>0</sup>C (Figure 3). In the -Ash location, the range was 21.50 – 25.59<sup>0</sup>C and 18.79 – 31.48<sup>0</sup>C, respectively.

### *Litter Quality*

The quality of fine roots classified by total N, lignin, and polyphenols content (Table 3).

### *Root decomposition*

An analysis of variance of the remaining dry weight after eight weeks (Table S1) showed that species, location, and season effects were highly significant ( $P < 0.001$ ), but the existing tendency towards slower decomposition at a larger distance from the nearest coffee tree was not ( $P = 0.06$ ). Further analysis of possible interactions between a distance effect, species, seasons and sites showed an average effect size of +1% and +5% for distances 0.5 and 1 m, and -8% for 1.5 m, respectively, on the derived decomposition constant  $k$ . Estimated relative effect size on  $k$  was less than +10 and more than -10%, except for two out of thirty estimates for species by season and site combinations. Only in the wet season in the +Ash site was the absolute effect size estimate larger than 20% (at -23%). Relatively small effects of location within the agroforestry system cannot be ruled out, but is unlikely to influence the comparison between seasons, sites, and tree species.

The regression of remaining dry weight against time accounted on average for around 90% of the variation in the data (minimum 87, maximum 93) (Table 4). The standard errors of the mean of the  $k$  estimates (ignoring distance effects) were about 8.2% of the estimates (minimum 6.1, maximum 11.0%), indicating a conservative limit to effect sizes that could be distinguished in the data set as 16%. The mean residence time across species as measured was 5.5 weeks (minimum 4.0, maximum 7.5 at the location \* season level), but after converting to a standard temperature of 20<sup>0</sup>C, the range was narrowed and the average increased to 7.5 weeks (minimum 6.4,

maximum 8.7), with resulting effect sizes of maximum + or – 15% just below what can statistically be distinguished from zero.

Using the distance to the nearest coffee tree as background variability, an analysis of variance (Table 5) confirmed highly statistically significant main and first-order interaction effects involving the factor tree, but statistically non-significant season-by-location and second-order interactions.

The ratio of S.E.D and mean was 3.08% for season and location, and 5.33% for tree as main effects, and 7.55 for season-by-tree and location-by-tree interactions. Further inspection of the data showed that the primary contribution to the first-order interactions with tree species was the responses observed for parasponia. After correction for differences between sites and season in soil temperature, a significant effect was noted for five out of the six species (Fig. 4), with higher k values (faster decomposition) in the dry season and without ash, but the pattern for parasponia differed, with a non-significant effect in the opposite direction: faster decomposition in the wet season and in the presence of fresh ash (Fig. 5).

After correction for known temperature effects, decomposition in the +Ash site was slower than that in the -Ash site for five of the six species, across both seasons. On average, the mean residence time was increased by 1.5 and 1.6 weeks, for wet and dry season respectively. The ash effect sizes of 18 and 23%, respectively, allowed rejection of a no-effect null-hypothesis. At the species level, parasponia showed the smallest (or even negative) ash effect on decomposition rates (-1.2 and +0.76 week increase in mean residence time, respectively) and sengon and durian the largest effects (+6.5 and +5.1 weeks increase in wet season, but only +2.0 and +1.3 weeks increase in the dry season); for gliricidia the ash effect was most consistent between seasons (+3.0 and +2.7 weeks for wet and dry season, respectively).

Across sites and seasons, the mean residence time of roots of parasponia and gliricidia was 19% shorter than that for the average across species, avocado and coffee approximately at average rates (4% shorter and 6% longer mean residence time), and that of sengon and durian considerably longer (36 and 59%, respectively). The species effect was thus highly significant, statistically.

Across all species the (L+P):N quality indicator proved to be only a weak predictor of mean residence time, as the high index for avocado was not reflected in slower decomposition. Omitting the avocado data (Figure 6B), positive relationships between the (L+P):N index and mean residence time were found, with the strongest relationship for the -Ash dry season data.

## Discussion

Despite the considerable level of replication, the variability of the data was such that only effect sizes between species larger than 10%, and tree-by-season or tree-by-location effect sizes of 16% could be considered to be statistically significantly different from zero. Statistically significant interactions between tree species and either ash or season effects hinged on the different responses for the volcanic ash-adapted local tree parasponia, and the five commonly used agroforestry tree species.

Some further backgrounds on parasponia may help interpret this interaction (Ishaq et al. 2020a, b). Genetic and comparative genomics studies (van Velzen et al. 2018) have debated the emergence of rhizobium-based nodulation in a tropical volcanic ash environment (where all nutrients other than nitrogen are available) as

triggered by a loss of control over non-mycorrhizal root intruders in parasponia species, compared to their non-nodulating sibling species in the genus *Trema* that allowed taxonomically old nodulation responses to become expressed. Loss of selectivity in parasponia may involve a shift along the fungal collaboration gradient that, according to (Bergmann et al. 2020) dominates the root economics space in plants. High decomposition rates of fine roots may be another consequence of this loss of intruder control, especially in the early stages of decomposition when antimicrobial and anti-fungal plant defense mechanisms may still work. Hypotheses on such molecular dimension to the phenomena we observed will be open to testing. The high root turnover of an ash-adapted tree species will likely contribute to enhanced pedogenesis (turning 'ash' into 'soil') may appear to be a specific form of plant-soil feedback. However, rather than being functional for parasponia survival, the soil feedback may be a side-effect of a plant trait that assists parasponia in thriving in this environment, while also laying the basis for its successional demise when increased soil nitrogen concentrations allow its competitors (including a *Trema* species) to take over its dominant position in the vegetation (Ishaq et al. 2020b).

The soil carbon accumulation rate of the volcanic ash from the Kelud has been high. The  $C_{org}$  content in the Kelud volcanic ash in 2014 was very low, around 0.35% (Utami et al. 2017). Six years later the topsoil (0-15 cm) in the +Ash sites had become 1.7%, still below the 2.12% in the -Ash site (Table 2). Two other, unpublished, measurements of  $C_{org}$  were done at our +Ash research site of the same layer. A measurement in 2014 indicated a  $C_{org}$  of 0.87%, which may indicate that a 0-15 cm soil sample consisted of 70.6% of ash (of 0.35%  $C_{org}$ ) and 29.4% of soil of 2.12%  $C_{org}$ . Direct estimates of the thickness of the ash layer of around 10 cm are consistent with this estimate. Keeping the mixing ratio of ash and soil at this level, the  $C_{org}$  content of ash may have increased to 0.77% in 2017 (for a measured 1.17%  $C_{org}$ ) and 1.53% in 2019 (for a measured 1.7%  $C_{org}$ ). The relative contribution of fine root turnover to this  $C_{org}$  accumulation depends, beyond the measured decomposition rates, on the above- to belowground biomass ratio's and the relative residence time of leaves and roots as live biomass. In situ fine root turnover, however, is likely an essential contributor to soil C accumulation in these soils where fresh volcanic ash is converted to Andisols.

For several aboveground litter sources (only partially overlapping with our root study and including a number of species litter mixtures), decomposition rates were measured in the same study sites by Ishaq et al. (2020a). When compared against the (L+P):N ratio, the mean residence time for aboveground litter was at least three times longer than that for fine roots (Figure 7). It suggests that the roots' contribution to the addition of soil  $C_{org}$  content is higher than aboveground litter. Sari et al. (in review) who conducted an aboveground litter study in cacao agroforestry in Southeast Sulawesi, reported soil C below the litterbags at the end of the experiment (after 16 weeks) was higher than it should be. Additional input of belowground litter (roots) was suspected of contributing to these higher soil C. Faster decomposition of fine roots that we found in this study indicates that belowground litter may play an essential role in the addition of soil C content.

Palm and Sanchez (1991) classified the quality of organic matter as low and slow to be decomposed if the lignin content is >20% and/or polyphenols >4%; this applies to four of the six belowground litter sources, with gliricidia and parasponia as exceptions. As the root litter is in closer contact with soil than aboveground litter in aboveground litter bags, it is feasible that nitrogen concentrations are more readily equilibrated with soil nitrogen sources, and that they have less likely to constrain decomposer activity.

Soil temperature effects on decomposition rate may vary between tree species (Cortina and Vallejo 1994; Gill and Jackson 2000; Prescott et al. 2000). Beyond temperature, differences in soil moisture content may have

influenced the results (Solly et al. 2014). Earlier studies found that soil moisture and temperature are the main abiotic factors that affect the rate of root decomposition (Chen et al. 2002).

Relative to the literature on aboveground litter decomposition, quantitative studies of fine root turnover are less common, with literature reviews highlighting differences in above- and belowground decomposition rates in either direction. There may be some good reasons for the lack of root decomposition studies, as fine root material is harder to obtain and may be affected by the collection effort during washing and storage, with dry weight losses of 20-40% possible (van Noordwijk and Floris 1979; Grzebisz et al. 1989; van Noordwijk et al. 1994). Adjustments of the standard litter bag methodology are needed to ensure realistic conditions, but this is not a serious constraint. In a global review, Silver and Miya (2001) concluded that root chemistry appeared to be the primary controller of root decomposition, while climate and environmental factors played secondary roles, in contrast to previously established leaf litter decomposition models. Root decomposition rates are highest in the topsoil (Pries et al. 2018).

Sun et al. (2018) found that for the temperate forest in China, decomposition rates for tree roots ( $k = 0.11 \pm 0.01$  years<sup>-1</sup>; which is fifty times slower than our results) were three times lower than those for leaf litter ( $0.35 \pm 0.02$  years<sup>-1</sup>). The considerably faster decomposition of aboveground litter than that of roots in a mangrove ecosystem documents by van der Valk and Attiwill (1984) was attributed to the comminutor role of crabs for aboveground litter. In contrast, root decomposition of cereal rye and hairy vetch cover crops was faster than that of aboveground crops (Sievers and Cook 2018). Bardgett et al. (2014) found that root N content, Rhizobia and pathogens had strong positive effects on root decomposition rates, and specific root length (inversely related to root diameter) a weaker positive effect. In a meta-review of root decomposition studies for 279 plant species across 105 studies and 176 sites See et al. (2019) found that the best plant functional traits for predicting fine-root decomposition differ from those predicting leaf decomposition with mycorrhizal association and woodiness as best predictors of fine root decomposition rates. The rapid decomposition in our study of parasponia is of interest in this context as it has the only known rhizobium-based N<sub>2</sub> fixing symbiosis outside the Leguminosae family and is specialized to volcanic ash environments in the tropics (Ishaq et al. 2020b). Poirier et al. (2018) reviewed evidence that species differ in their belowground contribution to SOM stabilization. **Morphological traits** commonly measured, such as specific root length and root diameter, were found to poorly relate to stabilization mechanisms, but mycorrhizal presence was confirmed to be a factor. Root can be adaption and grow on low nutrient availability conditions such as volcanic ash with mycorrhizal fungi, associations with nitrogen-fixing microorganism, and root structures to exude carboxylates (Muñoz et al. 2010). Availability of P and N is the main factor contributes to the plant species successfully colonizing and surviving on volcanic substrates (Shoji and Takahashi 2002; Vitousek et al. 2010).

Jiang et al. (2021) found clear differences between arbuscular mycorrhizal (AM) and ectomycorrhizal (ECM) species in the traits that predict root decomposition rates among 30 tree species from either temperate or subtropical forests in China. Carbon-related traits (including lignin and cellulose concentrations) dominated in AM species, while nutrient-related traits (magnesium concentration) appeared to be the main controls in ECM species. As all the tree species in our experiment are AM species, the 'outlier' result for avocado, where despite a high (L+P):N ratio decomposition was relatively fast deserved further scrutiny. Herzog et al. (2019) showed that during two years of decomposition of pine roots succession in Switzerland, changes in the bacterial and fungal decomposer communities were associated with a decrease of easily degradable carbohydrates and a relative

increase in persistent compounds such as lignin. With the much faster decomposition process in our study, such succession will likely proceed faster as well, but remains to be documented.

Poirier et al. (2018) highlighted the need to evaluate root decomposition and root-C stabilization concomitantly over the long-term, considering simultaneously root litter quality, microbial products and properties of the soil matrix. Our snapshots of two stages in the conversion of volcanic ash with a low, to Andisols with high C<sub>org</sub> content will have to be continued to meet that target.

## Declarations

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## Tables

**Table 1.** Land use characterization of research location (+Ash: Tulungrejo, Ngantang; -Ash: Krisik, Gandusari)

| Location | Number of tree species | Number of trees/ha | Basal area (m <sup>2</sup> /ha) | Basal area dominant/total (%) |
|----------|------------------------|--------------------|---------------------------------|-------------------------------|
| + Ash    | 5                      | 1388               | 11.4                            | 32.8                          |
| - Ash    | 4                      | 1275               | 17.5                            | 30.7                          |

**Table 2.** Soil chemical characteristics in the topsoil (0-15 cm depth) at the two sites

| Location | pH (H <sub>2</sub> O) | pH (KCl) | Bulk density [g cm <sup>-3</sup> ] | C <sub>Org</sub> , [%] | Soil texture (%) |      |      |
|----------|-----------------------|----------|------------------------------------|------------------------|------------------|------|------|
|          |                       |          |                                    |                        | Sand             | Silt | Clay |
| (+) Ash  | 5.13                  | 4.61     | 0.93                               | 1.70                   | 49.3             | 40.9 | 9.7  |
| (-) Ash  | 5.23                  | 5.17     | 0.89                               | 2.12                   | 69.3             | 26.3 | 4.2  |

**Table 3.** Fine root quality characteristics of various selected tree species

| Tree species | Total N, % | Lignin, % | Polyphenols, % | L:N  | (L+P):N |
|--------------|------------|-----------|----------------|------|---------|
| Gliricidia   | 2.1        | 15.4      | 1.9            | 7.3  | 8.2     |
| Parasponia   | 1.6        | 16.4      | 3.4            | 10.5 | 12.7    |
| Avocado      | 0.8        | 33.9      | 7.9            | 42.4 | 52.3    |
| Coffee       | 1.8        | 33.9      | 3.8            | 18.8 | 20.9    |
| Sengon       | 1.3        | 13.3      | 5.5            | 10.2 | 14.5    |
| Durian       | 1.5        | 29.3      | 2.6            | 19.5 | 21.3    |

**Table 4. Decomposition constants  $k_{20}$  (equivalents at 20°C; week<sup>-1</sup>) and mean residence time (MRT, week) for root material of six sources in two seasons at +Ash and -Ash sites; the Standard Error of the Mean (SEM) is derived from the three k estimates for the three distances,  $R^2$  is the fraction of variance accounted for in a dataset across the three distances**

| Condition:     |                               | Wet, +Ash     |             | Wet, -Ash     |             | Dry, +Ash     |            | Dry, -Ash     |            |
|----------------|-------------------------------|---------------|-------------|---------------|-------------|---------------|------------|---------------|------------|
|                | Soil temp °C,<br><i>Index</i> | 21.87         | 1.159       | 23.17         | 1.284       | 25.98         | 1.603      | 25.80         | 1.661      |
| Gliricidia     | $k_{20}$ , <i>MRT</i>         | <b>0.1189</b> | <b>8.4</b>  | <b>0.1839</b> | <b>5.4</b>  | <b>0.1497</b> | <b>6.7</b> | <b>0.2534</b> | <b>3.9</b> |
|                | SEM<br>/estimate, $R^2$       | 0.0192        | 0.884       | 0.0655        | 0.834       | 0.0591        | 0.828      | 0.0459        | 0.909      |
| Parasponia     | $k_{20}$ , <i>MRT]</i>        | <b>0.2170</b> | <b>4.6</b>  | <b>0.1832</b> | <b>5.5</b>  | <b>0.1342</b> | <b>7.5</b> | <b>0.1468</b> | <b>6.8</b> |
|                | SEM<br>/estimate, $R^2$       | 0.2095        | 0.861       | 0.0557        | 0.838       | 0.0905        | 0.872      | 0.0405        | 0.934      |
| Sengon         | $k_{20}$ , <i>MRT</i>         | <b>0.1348</b> | <b>7.4</b>  | <b>0.1547</b> | <b>6.5</b>  | <b>0.1244</b> | <b>8.0</b> | <b>0.1399</b> | <b>7.1</b> |
|                | SEM<br>/estimate, $R^2$       | 0.1321        | 0.895       | 0.0774        | 0.863       | 0.0824        | 0.971      | 0.0374        | 0.930      |
| Durian         | $k_{20}$ , <i>MRT</i>         | <b>0.0984</b> | <b>10.2</b> | <b>0.1176</b> | <b>8.5</b>  | <b>0.1398</b> | <b>7.2</b> | <b>0.1563</b> | <b>6.4</b> |
|                | SEM<br>/estimate, $R^2$       | 0.1081        | 0.819       | 0.1270        | 0.873       | 0.1298        | 0.973      | 0.0882        | 0.939      |
| Coffee         | $k_{20}$ , <i>MRT</i>         | <b>0.0668</b> | <b>15.0</b> | <b>0.1178</b> | <b>8.5</b>  | <b>0.1017</b> | <b>9.8</b> | <b>0.1272</b> | <b>7.9</b> |
|                | SEM<br>/estimate, $R^2$       | 0.0918        | 0.886       | 0.1065        | 0.891       | 0.0459        | 0.876      | 0.1223        | 0.942      |
| Avocado        | $k_{20}$ , <i>MRT]</i>        | <b>0.0569</b> | <b>17.6</b> | <b>0.0805</b> | <b>12.4</b> | <b>0.1032</b> | <b>9.7</b> | <b>0.1192</b> | <b>8.4</b> |
|                | SEM<br>/estimate, $R^2$       | 0.0966        | 0.961       | 0.0633        | 0.911       | 0.0422        | 0.981      | 0.0313        | 0.914      |
| <i>Average</i> | $k_{20}$ , <i>MRT</i>         | <b>0.1155</b> | <b>8.7</b>  | <b>0.1396</b> | <b>7.2</b>  | <b>0.1255</b> | <b>8.0</b> | <b>0.1572</b> | <b>6.4</b> |
|                | SEM/estimate, $R^2$           | 0.1096        | 0.884       | 0.0826        | 0.868       | 0.0750        | 0.917      | 0.0610        | 0.928      |

**Table 5. Analysis of variance of the main factors and first and second-order interactions of the decomposition constant k (equivalent at 20°C), using the three distances to coffee tree as background variation**

| Source of variation    | d.f. | s.s.      | m.s.      | v.r.   | F pr. | S.E.D.  |
|------------------------|------|-----------|-----------|--------|-------|---------|
| Blocks stratum         | 2    | 0.0036923 | 0.0018461 | 2.93   |       |         |
| Blocks.*Units* stratum |      |           |           |        |       |         |
| Season                 | 1    | 0.0822432 | 0.0822432 | 130.42 | <.001 | 0.00592 |
| Location               | 1    | 0.0369055 | 0.0369055 | 58.52  | <.001 | 0.00592 |
| Tree                   | 5    | 0.1380002 | 0.0276    | 43.77  | <.001 | 0.01025 |
| Season.Location        | 1    | 0.0000535 | 0.0000535 | 0.08   | 0.772 | 0.00837 |
| Season.Tree            | 5    | 0.0486139 | 0.0097228 | 15.42  | <.001 | 0.0145  |
| Location.Tree          | 5    | 0.032014  | 0.0064028 | 10.15  | <.001 | 0.0145  |
| Season.Location.Tree   | 5    | 0.0055652 | 0.001113  | 1.77   | 0.139 | 0.0205  |
| Residual               | 46   | 0.0290083 | 0.0006306 |        |       |         |
| Total                  | 71   | 0.376096  |           |        |       |         |

d.f. = degrees of freedom; s.s. = sum of squares; m.s. = mean square; v.r. = variance ratio; F pr = probability of the F statistic; S.E.D. = standard error of differences

## Figures

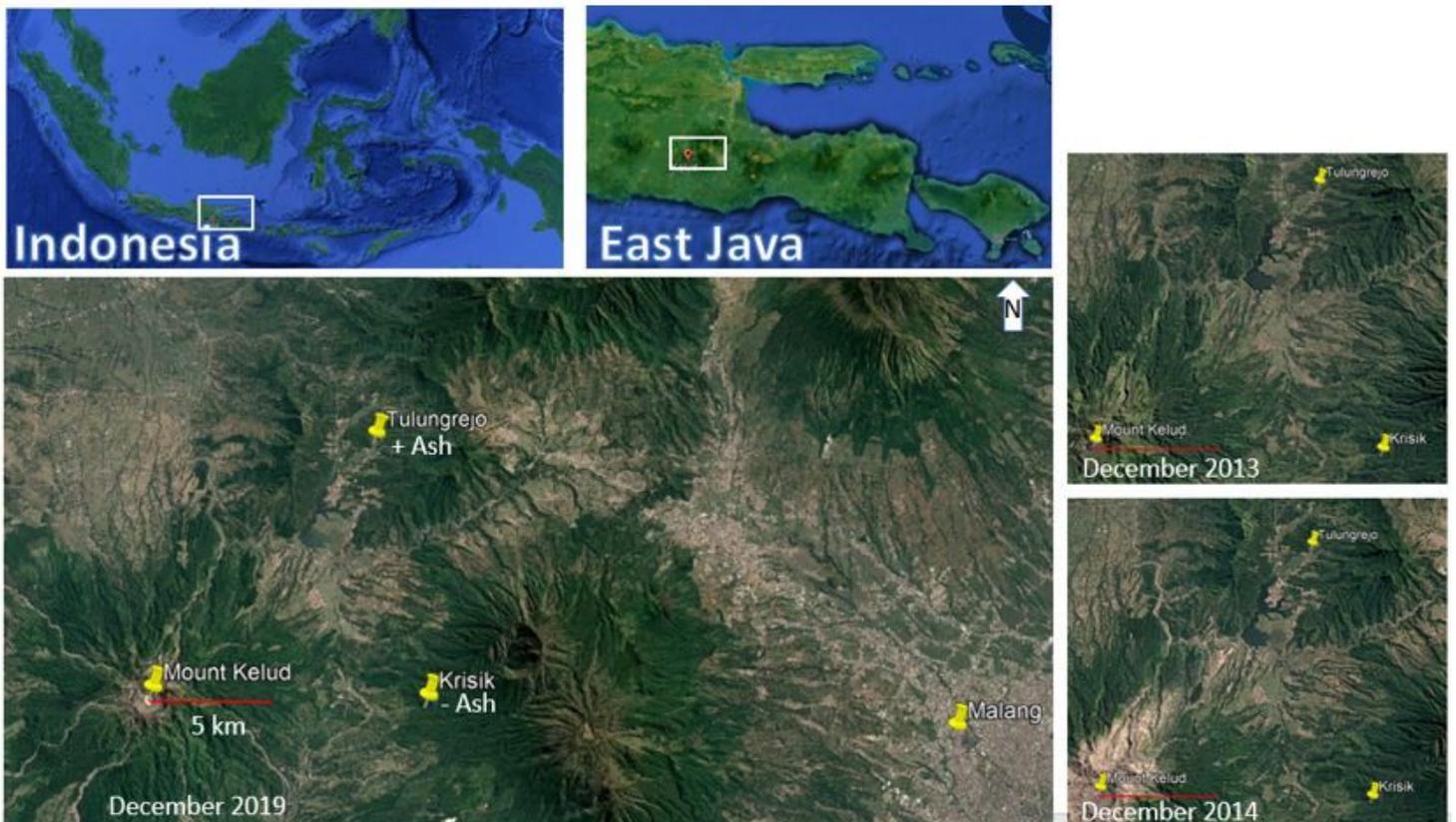
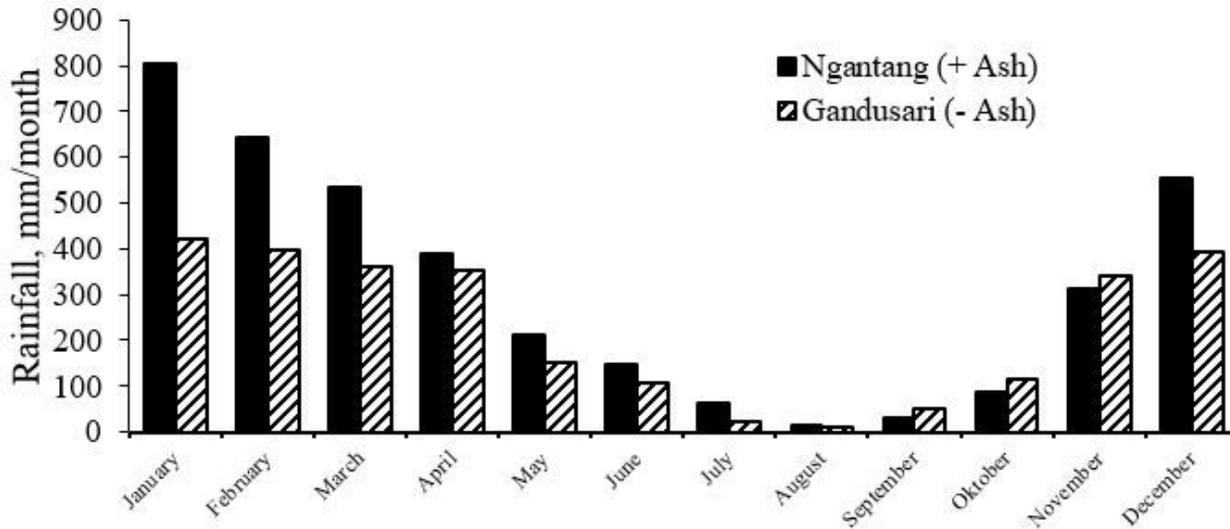


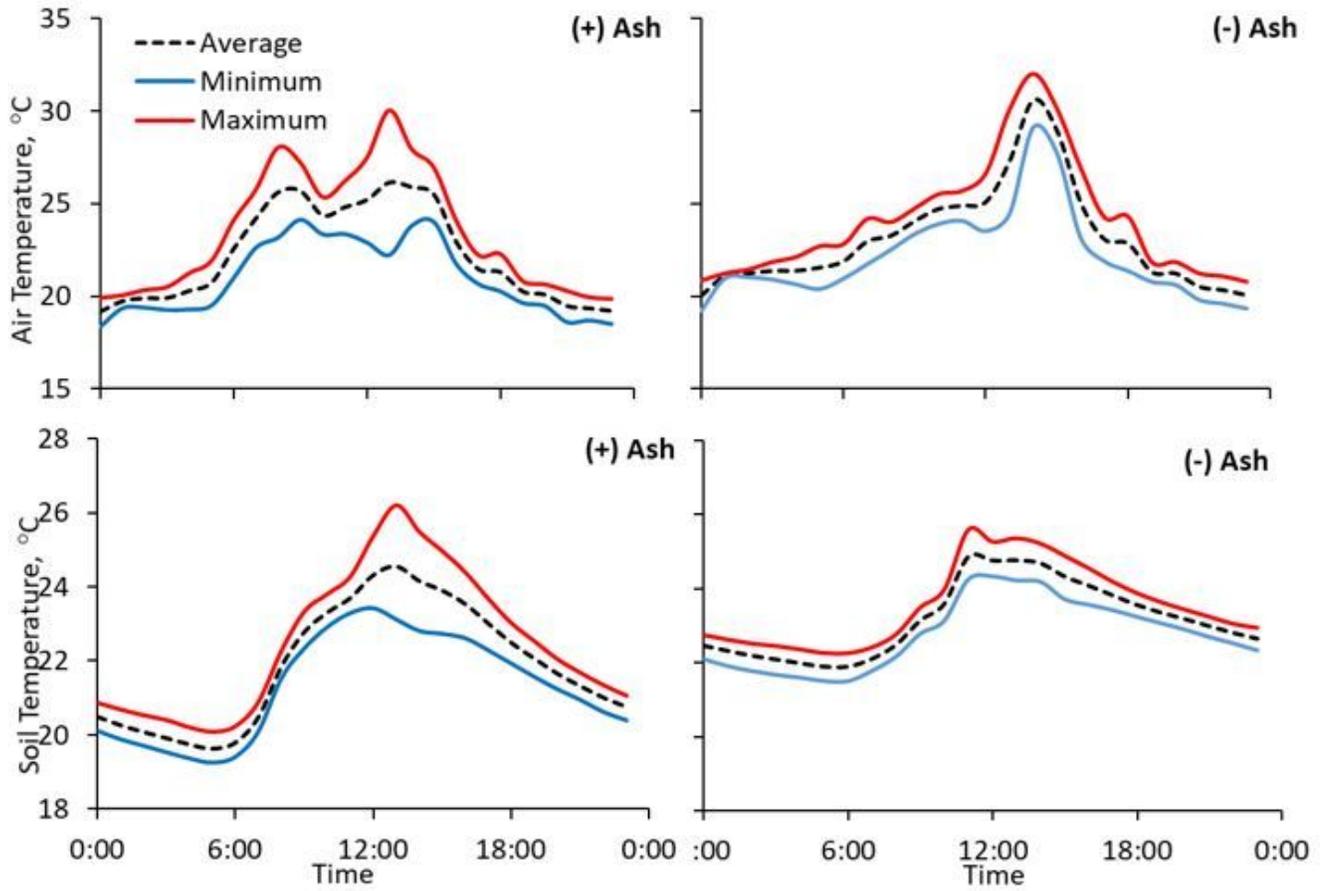
Figure 1

Surroundings of Mount Kelud (East Java, Indonesia) with research sites on which ash was deposited in the 2014 eruption (Tulungrejo, +Ash; 14.4 km NE) or not (Krisik, -Ash; 11.4 km E); Google.Earth imagery December 2019; details for December 2013 and 2014 represent the situation before and just after the eruption, with a NE direction of the ash plume



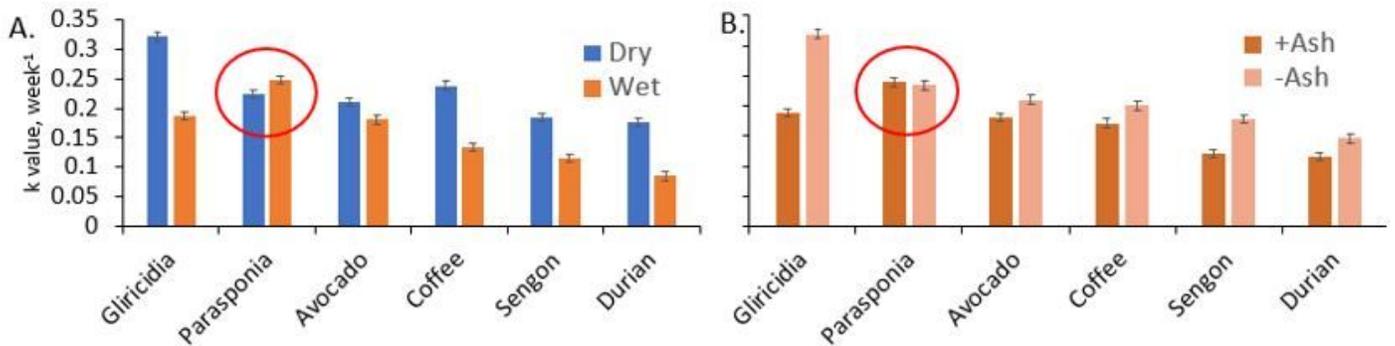
**Figure 2**

Monthly average rainfall in 2012-2019 in Ngantang District, Malang (+Ash) and Gandusari District, Blitar (-Ash); data source: Meteorology, Climatology and Geophysics Agency (BMKG) Karangploso Station



**Figure 3**

Air and soil temperature (at 15 cm depth) in two research sites during the decomposition measurements (8 weeks).



**Figure 4**

First-order interactions between tree species and A. season and B. location, with the standard error of differences of Table 5 indicated

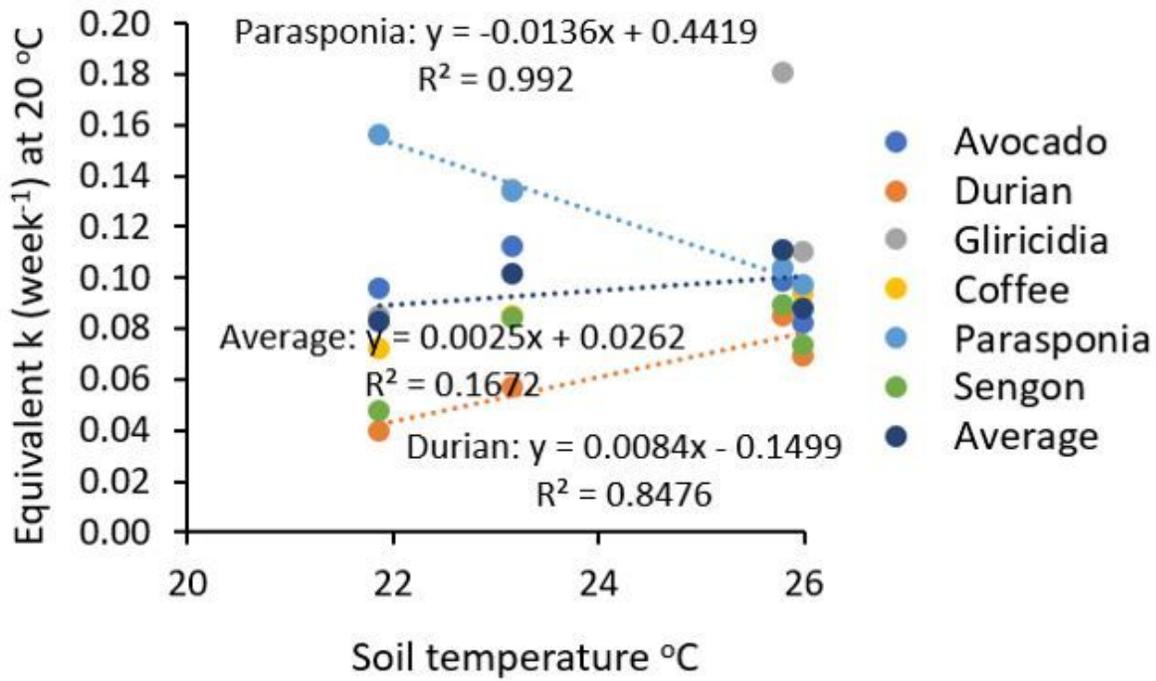


Figure 5

Residual relationship between soil temperature and an equivalent k value at 20°C (using a Q<sub>10</sub> value of 2.2)

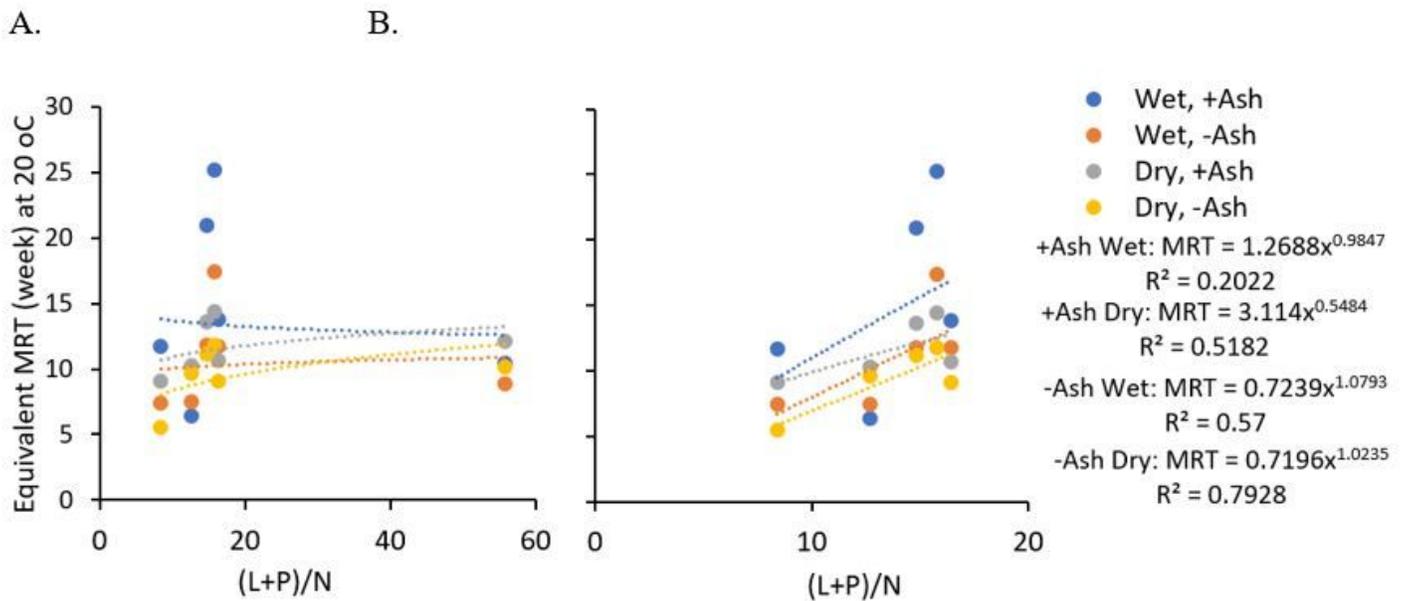


Figure 6

Relationship between litter quality (ratio of (L+P):N) and the equivalent mean residence time at 20°C; A. across all species, B. Omitting avocado

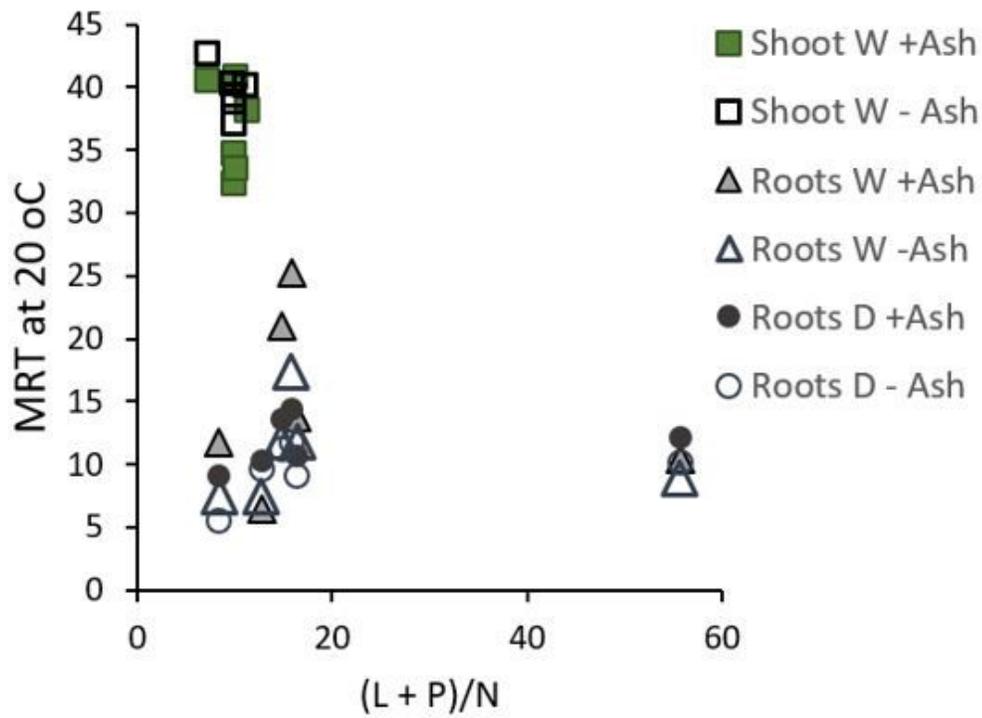


Figure 7

Mean residence time of tree leaves (Ishaq et al. 2020a) and roots (this study) in the same study area

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryTableS1andS2.docx](#)