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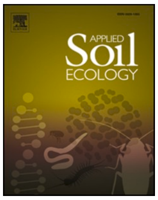

Traditional and cover crop-derived mulches enhance soil ecosystem services in apple orchards

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ABSTRACT

Organic mulches are a traditional method of groundcover management in temperate commercial orchards, now largely replaced by herbicides and synthetic fertilisers. As a potential contribution to improving orchard sustainability, we hypothesised that the addition of organic mulches would: (H1) improve soil fertility and lead to greater tree growth and yields; (H2) support a larger and more biologically active community of soil organisms, assessed as increased soil respiration and greater earthworm numbers and biomass; and (H3) increase leaf litter decomposition and burial, potentially reducing the risk of apple scab disease (*Venturia inaequalis*). Cuttings from two legume-based cover crop mixtures grown in the alleyway spaces between tree rows and two traditional mulch materials, straw and compost, were trialled alongside a bare soil business-as-usual control for two years, using a randomized complete block design in a conventionally managed commercial 'Gala' apple orchard in the UK.

Compared to the control, the compost mulch significantly increased both soil carbon and nitrogen by over 50 %. The straw mulch effectively suppressed weeds by about 90 % and increased soil moisture by about 5 %. Cover crop cuttings increased moisture levels and increased earthworm numbers and mass by 1.7 and 1.8 times greater respectively in the double-rate 'legume-grass' cuttings treatment. Increasing the quantity of cover crop cuttings produced more positive effects; the cumulative addition of cuttings can benefit several soil-derived ecosystem services. This study took place in a commercial apple orchard, the findings may therefore be applicable to other orchard and row-grown perennial crops.

1. Introduction

Orchard floor management is crucial for maintaining soil fertility and controlling weeds (Hogue and Neilsen, 1987; Merwin et al., 2003), but it can also significantly affect soil biota and ecosystem services. Many commercial orchards currently rely on intensive management regimes to maintain soil fertility, including synthetic fertiliser spreading and fertigation lines. A bare soil 'weed strip' or 'herbicide strip' is generally maintained underneath the tree rows to reduce competition for water and nutrients. In UK commercial apple (*Malus domestica*) orchards, a 1–2 m wide weed strip centred on the tree row is common, with mown grass alleyways maintained between the rows (Merwin et al., 2003). A 2 m^2 vegetation-free area around the trunk is generally considered sufficient to prevent competition with tree roots (Merwin and Ray, 1997; Neilsen and Hogue, 2000), though there has been relatively little research on this subject. Maintaining areas of bare soil can negatively impact soil health and increase weed pressure as it provides an empty niche for weeds. In addition, keeping areas of bare soil can lead to erosion, loss of soil organic matter, and adverse effects on soil physicochemical properties and soil biota (Gómez et al., 2009; Keesstra et al., 2016; Merwin and Stiles, 1994; Ramos et al., 2010; St. Laurent et al., 2008; van Capelle et al., 2012; Yao et al., 2005). Synthetic geotextile mulches and polypropylene sheets are sometimes used as alternatives. Although these can be effective at suppressing weeds and reducing soil moisture loss (Walsh et al., 1996; Żelazny and Licznar-Małańczuk, 2018; Zheng et al., 2017), they can be expensive and have environmental issues (Kader et al., 2017; Kasirajan and Ngouajio, 2012), including the reduction of beneficial soil biota such as earthworms and

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microfauna (Andersen et al., 2013; Neilsen et al., 2003a).

The impact of weed management on soil biota is important in orchards because it can interfere with important ecosystem services (Mathews et al., 2002). Soil-dwelling organisms provide a range of ecosystem services including soil structural improvements (Blouin et al., 2013), nutrient cycling (Beare et al., 1997; Germer et al., 2017; Tagliavini et al., 2007), pest regulation (Miñarro and Dapena, 2003; Suckling et al., 2006; Tuovinen et al., 2006), and pathogen control through the decomposition of crop-plant material (Glover et al., 2000; Holb et al., 2006; Jacometti et al., 2007a; Raw, 1962). The enhanced decomposition of leaf litter from the orchard floor contributes to an important sanitation service in apple production because it can reduce the prevalence of diseases such as apple scab (*Venturia inaequlais*), and thus lower the need for pesticide applications (Chatzidimopoulos et al., 2020; MacHardy, 1996; MacHardy et al., 2001). Currently, there is significant reliance on fungicides for apple scab control in many apple-growing regions, but there is both a growing pathogen resistance to chemical control and an increased stakeholder desire to reduce pesticide use (Carisse and Dewdney, 2002; Chapman et al., 2011).

Mulching with organic materials is a potential alternative to the bare-soil management used in many conventional orchards. As well as suppressing weeds, organic mulches have the potential to boost soil fertility, and improve soil health and ecosystem services (Hogue and Neilsen, 1987). Traditionally, organic materials such as straw, compost, and farmyard manure were applied as mulch under orchard trees. However, these materials are bulky to transport and apply, limiting their feasibility in commercial orchards. An alternative is to produce mulches within the orchard system itself. ‘Living mulches’ show some promise: specific plant species are deliberately grown across the orchard floor or in the weed strips under the trees. This has beneficial effects on soil fertility and soil biota, however the proximity of living mulches to tree roots may lead to excessive competition (Favretto et al., 1992; Hoagland et al., 2008; Mullinix and Granatstein, 2011; Qian et al., 2015; Sánchez et al., 2007; Żelazny and Licznar-Małańczuk, 2018), or to damage from rodent pests (Sullivan et al., 2018; Wiman et al., 2009). As a solution, cover crops can instead be grown in the alleyway spaces between tree rows and not directly underneath the trees. The cuttings from alleyway cover crops can be spread onto the ground under the trees using side-discharging mowers. This method is sometimes referred to as ‘mow and blow’ or ‘mow and throw’ (Granatstein and Sánchez, 2009; Pavek and Granatstein, 2014; Sarrantonio, 1992; Sirrine et al., 2008) and has been shown to help reduce weed abundance in vineyards (Steinmaus et al., 2008). Currently, alleyway vegetation in most commercial orchards consists predominately of grasses regularly mown to a short height, with cuttings left in the alleyways (Merwin et al., 2003; Walgenbach et al., 2021). Only small modifications to existing equipment or the replacement of standard mowers for side-discharging models would allow growers to adopt the ‘mow and blow’ cover crop mulching method.

The ability of legumes to fix nitrogen from the atmosphere can be exploited, were they added to these mixes (Granatstein et al., 2017; Mullinix and Granatstein, 2011; Sirrine et al., 2008; TerAvest et al., 2010; Tutua et al., 2002). The addition of plant-based mulches can also help to support soil quality and soil biota (Nakamoto and Tsukamoto, 2006; Ramos et al., 2010; Thomson and Hoffmann, 2007; Zheng et al., 2018a), potentially sustaining a larger community of detritivores and decomposers which can then increase leaf litter decomposition rates and reduce pathogen abundance (Jacometti et al., 2007b). In addition, the living cover crops themselves may also benefit soil functional diversity through their nutrient-rich root exudates (Jiao et al., 2013), increased soil carbon (Steenwerth and Belina, 2008), and interactions with mycorrhizal fungi (Baumgartner et al., 2005; Turrini et al., 2017). Above ground, diverse alleyway vegetation can also provide habitat and resources for pollinators (García and Miñarro, 2014; Saunders et al., 2013) and natural enemies of apple pests (Berndt et al., 2006; Markó et al., 2012; Staton et al., 2021; Tschumi et al., 2016).

The aim of this study was to test the effects of both traditional and cover crop-derived mulches on apple production and soil-based ecosystem services. The study evaluated three hypotheses using a range of parameters. Hypothesis 1: the addition of mulch improves soil fertility and physical conditions, which, in turn, improves tree growth and yields; parameters included soil carbon and nitrogen, weed and mulch cover in the weed strip, soil moisture and temperature, and tree response and yield. Hypothesis 2: organic mulch helps to support a larger and more biologically active community of soil organisms; parameters included soil respiration rates and earthworm mass and abundance. Hypothesis 3: more soil biota leads to more rapid leaf litter decomposition; parameters included leaf decomposition rates, both when exposed to all detritivores and when macroinvertebrates were excluded. We trialled municipal compost, wheat straw, and cuttings taken from two cover crops grown in orchard alleyways, alongside a bare soil business-as-usual control. The cover crop treatments consisted of two different mixtures of legumes and grasses, each applied at two different rates: the amount of material produced from the adjacent 1.5 m wide alleyway space, and double this amount to mimic the effect of greater mulch production. The latter being applicable to orchards with wider alleyways and/or narrower weed strips, as well as the build-up of cuttings that can occur during the lifetime of orchards (c. 20 years) (Weibel et al., 2003; Yao et al., 2005).

2. Methods

2.1. Study site

Fieldwork took place between June 2015 and May 2017 in a commercial apple orchard planted in 2012 near Sutton Valence, Maidstone, Kent, England. The orchard was established on a clay loam soil (33 % clay, 46 % sand, and 21 % silt) with a pH of 7.1–7.5. Topsoil (0–10 cm depth) nutrient availability was: phosphorus at 63.0 mg l^{-1}, potassium at 455.0 mg l^{-1}, and magnesium at 117.0 mg l^{-1}. Apple variety was ‘Gala’, the most common variety grown in the UK, grafted onto ‘M9’ rootstocks. The orchard was managed conventionally with drip fertigation lines under each row of trees. Tree spacing was 1 m within the row and 3.5 m between rows. A 2 m wide weed strip was centred on the tree row with a 1.5 m wide alleyway strip of mown vegetation, predominately perennial ryegrass (*Lolium perenne*). The weed strips in all plots were sprayed with herbicide in May/June and December/January at commercial rates. Alleyways were mown to a height of 5 cm every 7–10 days between March and August, with cuttings left in the alleyways. Excluding the application of mulches, the management of trees and groundcover followed established commercial practice.

2.2. Mulch treatments

Seven mulch treatments (Table 1) were tested using a randomized complete block design. Experimental plots consisted of three trees within a 4 m long by 2 m wide area of weed strip. Treatment plots were replicated in nine blocks across three tree rows, with each row containing three blocks, 63 plots in total. Plots were separated by 2 m within a row or by one alleyway between rows, and blocks were separated by 7 m within the row or one alleyway between rows.

The cover crops were not grown in the alleyways adjacent to the plots. Instead, the cuttings were collected from nearby ‘donor’ alleyways. The ‘oversown-clover’ treatment consisted of the established alleyway grasses, predominately perennial ryegrass (*Lolium perenne*), which were over-sown with a seed mixture of 75 % white clover (*Trifolium repens*) and 25 % black medic (*Medicago lupulina*) at a rate of 3.4 kg ha^{-1} of alleyway grass strip. Alleyways were disc-harrowed twice in early May 2014 before hand-broadcasting of seed and ring-rolling to ensure good seed-soil contact. The ‘legume-grass’ treatment was an alleyway sward mixture sown at 10.7 kg ha^{-1} of alleyway grass strip, with 72 % lucerne (*Medicago sativa*), 8 % red clover (*Trifolium pratense*),

Table 1
Details of mulching treatments. Detailed treatment descriptions can be found in the Methods Section 2.2. DM = dry mass. Spreading costs are estimated from Nix (2014), compost price is based on figures from WRAP (2008), and straw price is based on AHDB figures. Estimated costs are per hectare, based on orchards with 2 m wide weed strips and 1.5 m wide alleyways.

Treatment	Estimated quantity added per application, per m^2 of weed strip	C and N content of mulch	Number of applications	Estimated cost of application (per hectare)	Estimated cost over lifetime of orchard (c20 years)
Control	NA	NA	NA	NA	NA
Straw	2062.5 g DM, 18.75 l	40.7 % C 0.9 % N	One – June 2015	Mulch: 11.8 t at £65 per tonne = £767 Spreading: £108–£147 Total: £875–£914	Re-apply every 3 years Total: £5250–£5484
Compost	9750 g DM, 18.75 l	23.2 % C 1.6 % N	One – June 2015	Mulch: 56 t at £6–20 per tonne = £336–£1120 Spreading: £72–98 Total: £408–£1218	Re-apply every 3 years Total: £2448–£7308
Oversown-clover	215 g DM (equivalent to 1 m of alleyway arisings)	39.7 % C 2.1 % N	Six (three annually) – June 2015 (double rate applied), August 2015, May 2016, June 2016, August 2016	Ground preparation (disking) and seeding Total £61	If allowed to seed re-sowing may not be needed. Total: £61
Oversown-clover2	430 g (equivalent to 2 m of alleyway arisings)	39.7 % C 2.1 % N	Six (three annually) – June 2015 (double rate applied), August 2015, May 2016, June 2016, August 2016	NA	NA
Legume-grass	247.5 g DM (equivalent to 1 m of alleyway arisings)	32.3 % C 1.1 % N	Six (three annually) – June 2015 (double rate applied), August 2015, May 2016, June 2016, August 2016	Ground preparation (herbicide, disking, harrowing) and seeding Total £153	Re-sowing may be needed every 4–5 years. Total: £765
Legume-grass2	495 g DM (equivalent to 2 m of alleyway arisings)	32.3 % C 1.1 % N	Six (three annually) – June 2015 (double rate applied), August 2015, May 2016, June 2016, August 2016	NA	NA

12 % Cocksfoot grass (*Dactylis glomerata*), and 8 % Timothy grass (*Phleum pratense*). For this treatment, alleyways were sprayed with glyphosate one week before disc-harrowing twice and power harrowing once in early May 2014. Seed was then broadcast by hand before ring-rolling.

Vegetation in the donor alleyways was surveyed once per month between April and August in 2015 and 2016, using 6 randomly placed 0.75 × 0.5 m subplots per plot. The percentage cover of each plant species was visually estimated, and four measurements of vegetation height were taken for each subplot using the direct measure method (Stewart et al., 2001). The 'oversown-clover' alleyways had a mean percentage cover of 65 % volunteer grasses, 56 % white clover, 3.9 % other plants, and 5.4 % bare soil, with a mean sward height of 14.5 cm. In the 'legume-grass' alleyways, the vegetation cover was 49 % cocksfoot, 2 % timothy, 1.3 % lucerne, 0.4 % red clover, 26.5 % volunteer grasses, 18.6 % other plants, and 9.4 % bare soil, with a mean height of 18.4 cm. Donor alleyways were mown three times annually: in May, June, and August. These dates were chosen in an attempt to maximise mulch yields, with at least one month left between cuts to allow cover crops to regrow. Cover crops were cut to 10 cm height using a modified rotary mower (DR PRO42) with a discharge chute used to collect arisings. Cuttings were then moved to the experimental plots and applied by hand on the dates shown in Table 1. Due to a delay in site preparation, the first application of cuttings, planned for May 2015, could not be applied on time, and so double rates were applied in June 2015. The compost used in this study was a commercially available municipal compost adhering to BSI PAS 100 standards (WRAP, 2011), with a particle size of 0–10 mm. The straw was conventionally grown wheat straw.

The mass of cover crop mulch applied was estimated by weighing fresh cuttings; subsamples were dried and reweighed to establish dry matter content. The weights of compost and straw shown in Table 1 are based on supplier estimates. Four subsamples of each mulch material were collected, dried, milled, and weighed to 10 mg (± 0.3 mg) before percentage C and N were measured using a Flash 2000 CN analyser (Thermo Scientific, Waltham, USA) (Table 1).

2.3. *Ecosystem service parameters*

2.3.1. *Soil carbon and nitrogen*

Soil cores were taken at the end of the experiment in May 2017. A soil corer with a diameter of 2.5 cm was used to take 15–20 cores per plot to a depth of 10 cm. Cores from individual plots were pooled and mixed before air drying for at least 14 days. Samples were then milled, and a 10 mg (± 0.3 mg) subsample was used to determine percentage carbon and nitrogen for each plot using a Flash 2000 CN analyser (Thermo Scientific, Waltham, USA).

2.3.2. *Weed and mulch cover*

The percentage cover of plants growing in the weed strip was recorded in a 1 × 0.5 m subplot, covering the width of the weed strip from the alleyway to the tree row. All vascular plants growing in this area were considered weeds; moss cover was recorded but not included in the analysis. The percentage weed cover in one subplot per plot was recorded in June 2015, before mulch application, and then in May 2016, June 2016, July 2016, and April 2017. Although weeds were recorded to species this was not included in the analysis, with total vegetation cover used instead. Mulch cover was recorded at the same time. If mulch was applied in that month, subplots were surveyed before application.

2.3.3. *Soil moisture and temperature*

Soil moisture measurements were taken in August 2015, and April, May, June, July, and August 2016 up to a depth of approximately 6 cm using a ML2 ThetaProbe (Delta-T). Soil temperature was recorded in three of the nine blocks from July 2015 to March 2016, and August 2016 to April 2017 using iButton data loggers (Thermocron iButton, Maxim Integrated) buried at 5 cm depth.

2.3.4. *Tree response and yield*

In July 2015, digital callipers were used to take two trunk diameter measurements of every tree, the second measurement perpendicular to the first. Measurements were taken 50 cm above ground level at a point permanently marked with an oil-based marker. In April 2017 measurements were repeated at these marks to establish trunk expansion as a proxy for tree biomass growth. In July 2016 a chlorophyll meter (Konica Minolta SPAD-502Plus) was used to record the chlorophyll content of five leaves per tree (15 leaves per plot). The total number of fruit on each tree was recorded one to two weeks before commercial harvest. Ten apples per tree (30 fruit per plot) were randomly selected and their diameters recorded; of these three were collected for further quality assessments (nine fruit per plot). Quality measures included: number of seeds, fresh weight, firmness using a Silverline penetrometer, soluble solids or Brix using a Hanna refractometer, and dry weight (entire fruit were cut into four pieces and oven-dried at 70 °C for at least 72 h before reweighing). In total 1134 fruit were assessed for this study: nine fruit from each of the 63 plots in both 2015 and 2016.

2.3.5. Soil respiration

Soil respiration rate was used as a proxy of soil biological activity and was recorded using an infra-red gas analyser (LCi-SD IRGA, LCi Photosynthetic System, ADC Bio Scientific Ltd. UK) with a soil chamber attachment placed directly onto the soil surface. Measurements were taken alongside soil moisture measurements: once per month in August 2015, and April, May, June, July, and August 2016. Respiration rates were calculated as the net molar flow of CO_2 into or out of the soil (C_e (p mols s^{-1}), where:

$$C_e = u\,(-\Delta c)$$

u = molar air flow in mol s^{-1}

Δc = difference in CO_2 concentration through soil chamber, dilution corrected, *u*mol mol^{-1}.

2.3.6. Earthworm abundance

Earthworm sampling was conducted in April 2016. For each plot, a soil pit measuring 25 × 25 × 25 cm was dug in the weed strip, halfway between the tree line and the edge of the alleyway vegetation. The soil was spread on a 1.8 × 1.2 m tarpaulin and sorted by hand for 10 min; pilot studies in previous years had shown that 10 min of sorting resulted in an optimal balance between an accurate estimate of earthworm biomass and time allocation (Schmidt, 2001). All earthworms were collected and kept in pots containing moist paper towels for 48 h to pass their gut contents. The earthworms were then washed, blot-dried with paper towels, counted, and weighed. Pieces of earthworm were included in the weight measurements but were not counted.

2.3.7. Leaf decomposition

In December 2015, apple leaves were collected from the alleyways neighbouring the experimental plots. The leaves were air-dried until constant weight and then separated into 10 g (± 0.35 g) samples. The weight of each sample was recorded before being put into 20cm^2 plastic mesh bags with hole diameters of 2 mm. Two bags were placed flat on the ground in the weed strip of each plot to simulate natural leaf fall (126 bags in total). In October 2016, the bags were collected, and their contents were air-dried until constant weight before being reweighed. In December 2016, this process was repeated, with bags being collected in late April 2017.

In addition to the leaf litter bags put out in December 2016, individually weighed 10 g (± 0.5 g) leaf samples (two samples per plot) were collected and placed underneath 20 cm^2 plastic mesh covers with hole diameters of 20 mm. The covers were pegged down to prevent leaves from being blown away but allowed unrestricted access from the soil below the leaves. The leaves underneath these covers were therefore exposed to macroinvertebrates such as earthworms, whereas those in the bags were not.

Apple scab prevalence was not monitored on the experimental plots as airborne apple scab ascospores can be highly mobile (Aylor, 1998), and the orchard was being managed with a conventional fungicide regime which is likely to have confounded results.

2.4. Statistical analysis

Data were analysed using linear and generalised linear mixed effects models in R version 3.5.1. (R Core Team, 2017) using the “lme4” package (Bates et al., 2012). Treatment was the main fixed effect in all models, with original measurements included as covariates in the leaf litter weights and the trunk diameter models. “Block” was used as a random effect in all models, with “plot” and “bag” as nested random effects for the leaf litter bag models, and “tree” as a nested random effect for the trunk diameter and fruit count models. Sampling “month” was included as a crossed random effect in the soil respiration, soil moisture, and weed cover models, and “date” was used as a crossed random effect for soil temperature. Data from different years for fruit production and leaf litter decomposition were analysed separately. Generalised linear mixed effect models with a Poisson error distribution were used for both fruit number and earthworm number data. To compare treatments, pairwise *t*-tests of the significance of differences between least-squares means were conducted using the R package “lsmeans” (Lenth, 2016). Graphics were produced in R using the package “ggplot2” (Wickham, 2009).

3. Results

3.1. Soil carbon and nitrogen

Both soil carbon and soil nitrogen were significantly higher in the compost treatment compared to all other treatments (Fig. 1) ($p < 0.001$, pairwise least-squares means tests, $\alpha = 0.05$). There were no other significant differences between treatments.

3.2. Weed and mulch cover

Weed cover was significantly higher in the compost treatment (77.8 %), and significantly lower in the straw treatment (4.3 %) in comparison to all other treatments (Fig. 2A and C). The mean weed cover in the

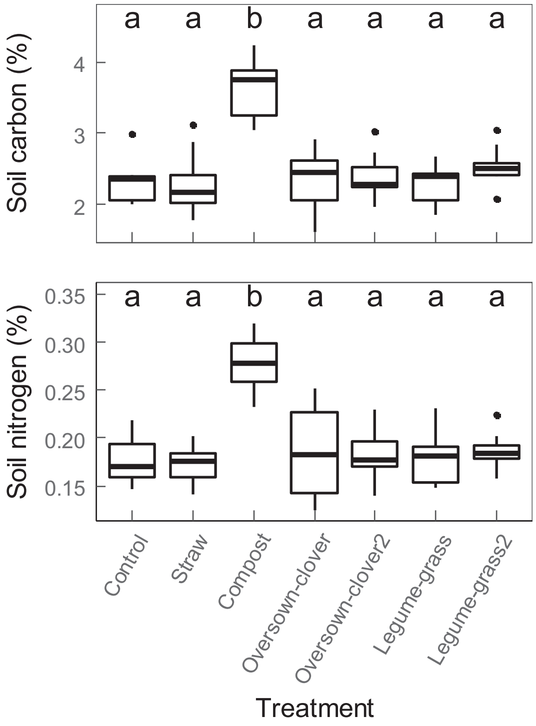

Fig. 1. Soil carbon and nitrogen percentages in orchard weed strips following mulching, taken at a depth of 0–10 cm. No mulch was applied in the Control treatment. Box plots denote median, quartile, and maximum and minimum values. Single data points are designated outliers. Means for treatments labelled with different letters are significantly different according to pairwise *t*-tests ($p < 0.05$).

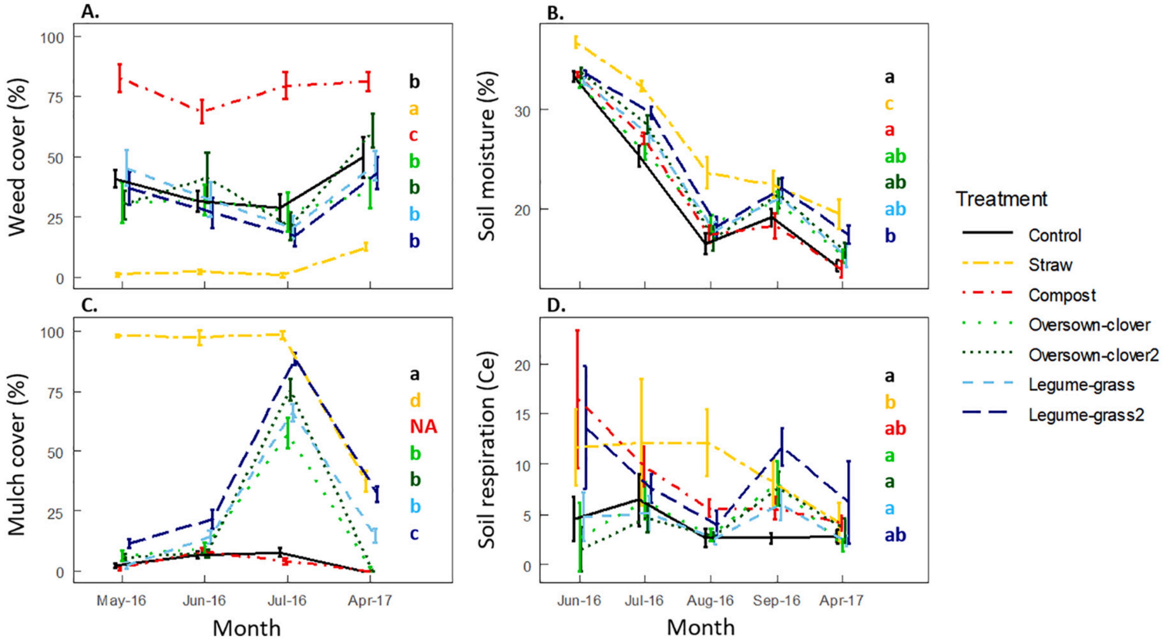

Fig. 2. A - Percentage weed cover, B - soil moisture (taken at a depth of approximately 6 cm), C - mulch cover, and D -soil respiration rates recorded at the soil surface in weed strips under different mulching treatments (mean ± SEM). The compost treatment was not included in the mulch cover analysis as the incorporation of compost into the soil made estimates unreliable. Group letters indicate significant differences across the whole sampling period, as calculated by pairwise least-squares means tests ($p < 0.05$). Letters are in the colour and order of the treatments shown in the legend. Straw and compost were applied once in June 2015, and cuttings from the 'oversown-clover', 'oversown-clover2', 'legume-grass', and 'oversown-grass2' treatments were applied in June and August 2015, and April, June, and August 2016.

'legume-grass2' plots, which had the second-lowest weed cover, was 31.1 %, with the control treatment having weed cover of 37.8 %. The most abundant plants growing in the weed strip were grasses (predominately perennial ryegrass, *L. perenne*), groundsel (*Senecio vulgaris*), cleavers (*Galium aparine*), and common nettle (*Urtica dioica*). Groundsel made up 39 % of weed cover across all treatments, and 64 % of weed cover in the compost treatment. The analysis of mulch cover shown in Fig. 2C does not include the compost treatment as the mixing of compost and soil made percentage cover estimates unreliable. The mulch cover values seen in the control and compost treatments were due to small amounts of grass cuttings from the adjoining alleyways being blown onto the weed strip.

3.3. *Soil parameters and tree response*

Over the length of the study, soil moisture was significantly higher in the straw treatment (with an overall mean of 26.9 %) when compared to all other treatments. Soil in the 'legume-grass2' treatment (mean 24.2 %) had significantly more moisture than both the control ($p < 0.001$) and compost ($p = 0.0025$) plots, which showed the lowest (mean 21.7 %) and second lowest (mean 22.1 %) moisture levels respectively (Fig. 2B).

There were no statistically significant differences between treatments in the daily mean or maximum soil temperatures. The straw treatment showed significantly lower daily minimum temperatures than the control ($p = 0.0056$), and a significantly reduced range in daily temperatures when compared to the control, 'oversown-clover', and 'oversown-clover2' treatments ($p = 0.019$, $p = 0.047$, $p = 0.026$ respectively).

The straw, 'legume-grass2', and compost treatments showed the highest rates of soil respiration during the monitoring period, with respiration in the straw treatments being significantly higher than the other four treatments (Fig. 2D).

No significant differences were found for tree growth, leaf chlorophyll content, estimated fruit yield, or any of the fruit quality measures.

3.4. *Earthworm abundance*

Earthworm abundance varied considerably between the treatments. The 'legume-grass2' treatment had 2.4 times the number and 3.4 times the weight of earthworms compared to the straw treatment, and 1.7 times the number and 1.8 times the weight compared to the control treatment (Fig. 3). Earthworms were significantly more numerous in both of the double rate cuttings treatments ('legume-grass2' and 'oversown-clover2') compared to the control, straw, and compost treatments. Significantly more earthworms were found in the 'legume-grass' treatment than the straw and compost treatments, with the straw treatment showing the fewest earthworms overall.

3.5. *Leaf litter decomposition*

For litter bags incubated between December 2015 and October 2016 (Fig. 4), the greatest reduction in leaf mass was seen in the 'legume-grass2' and compost treatments (with a mean of 2.16 g and 2.17 g remaining respectively). These two treatments showed significantly less leaf mass remaining when compared to the control and straw treatments (with 3.11 g and 3.35 g respectively). The 'oversown-clover2' treatment, which had an average of 2.44 g leaf mass remaining, also showed significantly more decomposition than the straw treatment. The bags that were incubated between December 2016 and April 2017 did not show any statistically significant differences between treatments. In both years the 'oversown-clover', 'oversown-clover2', and 'legume-grass' treatments showed similar amounts of leaf decomposition.

The leaf litter covers, which allowed macrofauna access to the leaves, showed 100 % removal of recoverable leaf litter fragments in all treatments between December 2016 and April 2017. This compares to an average reduction in mass of 40.4 % (4.07 g remaining) for leaves in litter bags over the same period.

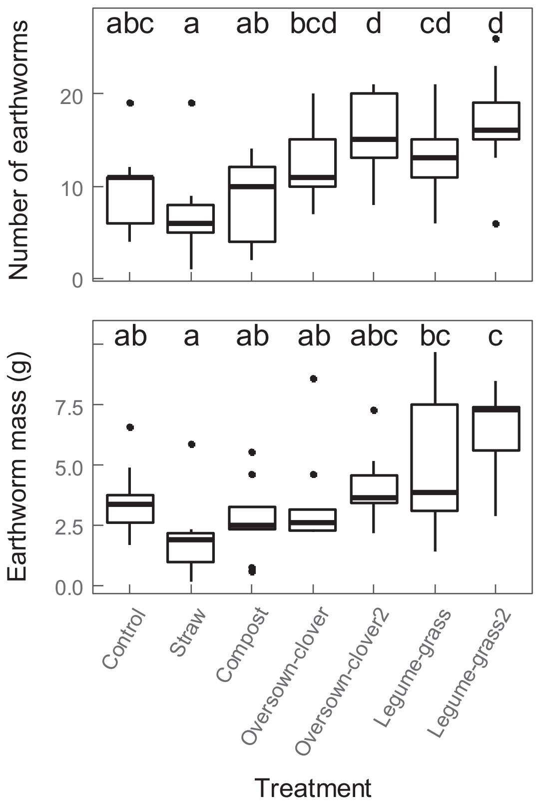

Fig. 3. Numbers and of biomass of earthworms per 25 × 25 × 25 cm soil pit taken from the weed strips of orchard plots under different mulching treatments. Box plots denote median, quartile, and maximum and minimum values. Single data points are designated outliers. Means for treatments labelled with different letters are significantly different according to pairwise *t*-tests ($p < 0.05$).

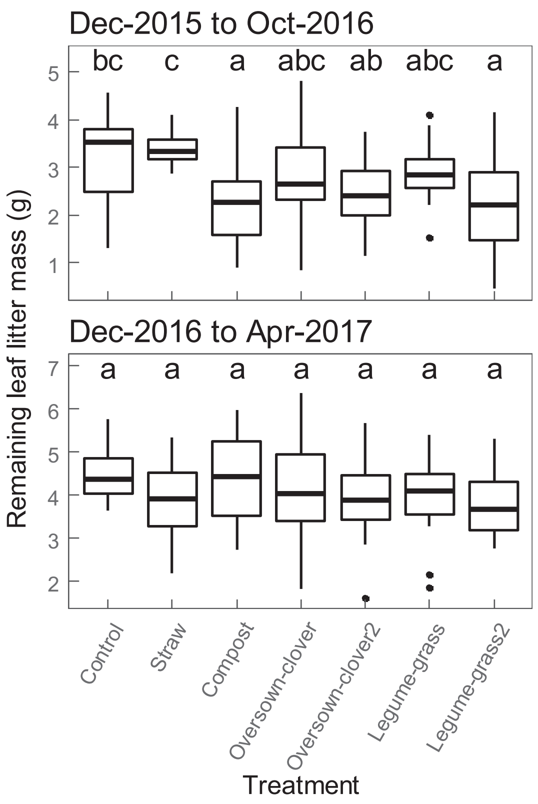

Fig. 4. Mass of leaf litter remaining in litter bags after 10 months exposure (Dec-15 to Oct-16) and five months exposure (Dec-16 to Apr-17) on the surface of orchard weed strips under different mulching treatments. Original weights of 10 g (± 0.5 g). Box plots denote median, quartile, and maximum and minimum values. Single data points are designated outliers. Means for treatments labelled with different letters are significantly different according to pairwise t-tests ($p < 0.05$).

4. Discussion

The results from this study show that whilst mulching can indeed improve some indicators of soil fertility and soil biological activity, the effects vary depending on the materials used (Table 2). The hypothesis (H1) that mulching positively affects soils was generally supported, though its benefits were not seen in all treatments. The compost treatment showed significantly higher soil carbon and soil nitrogen content compared to all other treatments, whilst the straw treatment appeared to have little effect on these parameters, despite having the second greatest mass of mulch material added after the compost treatment. This may be due to the degree of mixing with the soil which took place; the small particle size of the compost would have allowed easier incorporation into the soil compared to the long stalks of the straw. Studies show that mulching can increase soil moisture (Byers et al., 2003; Merwin et al., 1994; St. Laurent et al., 2008; Stefanelli, 2009), as was seen under the straw and ‘legume-grass2’ treatments. The high soil moisture levels, low soil temperatures, and low range in daily soil temperature seen in the straw treatment are likely to be due to the insulating effect of the straw, or its pale colour increasing light reflection and cooling the soils. Light reflected upwards from mulches can also increase colouring of fruit (Blanke, 2008; Meinhold et al., 2011), although no evidence of this effect was found in this study. The greater weed suppression provided by the straw treatment is another possible cause for the increased soil moisture as transpiration from weeds would have been reduced. The enhanced weed suppression shown in the straw treatment happened even though vegetation was already being controlled with herbicide. The application of compost, on the other hand, led to higher weed cover and the second-lowest soil moisture content. Although the weed cover was higher in the compost treatment, the most common species was groundsel (*S. vulgaris*), a shallow-rooted summer-annual, which may be less competitive with the trees than other weed species.

The alleyway cuttings did not improve weed suppression compared to the control. However, it is possible that if cuttings were repeatedly applied over several years, a litter layer may build up and could smother weeds in a similar way to the straw (Granatstein and Sánchez, 2009; Yao et al., 2005). Straw and layers of mulch covering bare soil may also help to reduce rain-splash, which is considered a potential route of soil and leaf litter pathogens (including apple canker, *Neonectria ditissima*) movement onto trees (Weber, 2014). During the timeframe of this study, mulching did not have a detectable effect on tree growth, leaf nitrogen, or yields, though other studies have shown that the addition of compost and wood-chips to the weed strip can positively affect tree growth and yields (Autio et al., 1991; Smith et al., 2000; TerAvest et al., 2010).

The hypotheses that mulching would increase the community of soil organisms (H2) and lead to greater leaf litter decomposition (H3) were also supported by our results. The control treatment, where no mulch had been applied, showed the lowest rates of soil respiration and the least leaf litter decomposition. However, only the straw treatment showed significantly higher soil respiration rates, and this did not translate into greater leaf litter decomposition rates as predicted. Apple leaves were lying on top of the layer of straw, whilst increased biological activity indicated by the higher respiration rates was likely occurring in the damper, lower layers of straw and soil. The faster leaf litter decomposition rates seen in the ‘legume-grass2’, ‘oversown-clover2’, and compost treatments may be due to the microbe communities in these plots being more abundant or active, although respiration rates

Table 2
Summary of results showing significant effects of mulching treatment compared to a bare soil business-as-usual control. Leaf litter decomposition refers to the bags incubated in 2015–2016 only. Symbols indicate significance as calculated using pairwise least square means tests ($p = 0.05$): '-' = lower than the control, '+' = greater than the control, and '0' = not significantly different from control. Long-term cost is an estimate of the cost per hectare over the lifetime of the orchard (see Table 1 for more details).

Treatment	Straw	Compost	Oversown-clover	Oversown-clover2	Legume-grass	Legume-grass2
Soil Carbon	0	+	0	0	0	0
Soil Nitrogen	0	+	0	0	0	0
Weed suppression	+	–	0	0	0	0
Soil moisture	+	0	0	0	0	+
Tree growth	0	0	0	0	0	0
Fruit yield and quality	0	0	0	0	0	0
Soil respiration	+	0	0	0	0	0
Leaf litter decomposition	0	+	0	0	0	+
Number of earthworms	0	0	0	+	0	+
Mass of earthworms	0	0	0	0	0	+
Long-term cost	£5250–£5484	£2448–£7308	£61	NA	£765	NA

were not significantly higher than in the control plots. In the case of the 'legume-grass2' and 'oversown-clover2' treatments, the microbe communities may have been better adapted to decomposing fresh plant material. Mulching can increase soil biological activity and positively alter the composition of soil microorganism communities (Forge et al., 2008; Pathan et al., 2021; St. Laurent et al., 2008; Watson et al., 2017; Yao et al., 2005; Zheng et al., 2018a, 2018b). By providing resources and a favourable habitat for decomposers and detritivore communities, mulch may improve leaf litter decomposition rates following leaf-drop in autumn. Mulching has been shown to reduce the sporulation of fungal pathogens, increase resistance to disease, and improve yields in vineyards (Jacometti et al., 2007b, 2007a). The lack of significant differences in leaf litter decomposition seen in 2016–2017 may be due to the reduced length of time that they were in the orchard; ten months in 2015–2016 versus just five in 2016–2017. The leaves under the leaf covers showed a far more rapid loss of mass over the same period, with no recoverable leaf litter fragments remaining. This supports the notion that macroinvertebrates, such as earthworms, are key for leaf litter removal and therefore for the biological control of apple scab.

The higher earthworm abundance seen in some of the mulched plots suggests that adding organic material to the weed strips can indeed help to support beneficial soil biota. The higher earthworm abundances in the 'legume-grass2' and 'oversown-clover2' treatments suggest that fresh vegetation cuttings are more valuable to earthworms than compost or straw mulches. Conversely, other studies have found that straw mulch can positively affect earthworm numbers (Andersen et al., 2013; Thomson and Hoffmann, 2007). The digestibility of different mulch materials is likely to vary for different earthworm species depending on their feeding niches. Epigeic (surface-dwelling) and anecic (burrowing) species (Bouch, 1977) more likely to feed on fresh material such as cover crop cuttings and apple leaves, than the species which generally feed on soil or compost (Blouin et al., 2013; Curry and Schmidt, 2007).

The estimated costs per hectare of the traditional mulches over the lifetime of an orchard were £5250–£5484 for straw and £2448–£7308 for compost (Table 1). The traditional mulch materials in this study became increasingly degraded and dispersed, and by the end of the experiment, they were visibly reduced. In particular, the percentage cover and weed suppression effectiveness of straw appeared to be waning. If the effects of the two traditional mulches were to continue throughout the lifetime of the orchard, they would need to be reapplied on a 3–4-year basis based on the decay rates seen in this study. Transportation and application of these mulches are costly, suggesting that their use would only be feasible if materials were locally available.

Although only the double-rate cover crop mulch treatments produced results comparable with traditional mulches, both cover crops had considerably lower estimated lifetime cost than traditional mulches (Table 1). They may therefore be a more environmentally friendly and cost-effective alternative. To gain the most benefit from alleyway cover crops, it will be important to manage them as an integral part of the orchard system: factoring in nutrient and water demands, considering the width of alleyways needed to produce the desired volume of mulch, and finding optimum mowing regimes and species mixtures. The cover crops themselves may also need to be replenished over time: white clover can survive indefinitely if allowed to seed, but lucerne may need to be re-sown every 4–5 years (AHDB, 2014). The 'legume-grass' mixture produced more dry mass of cuttings than the 'oversown-clover' mixture, but had a lower species cover of legumes in the sward. The 'legume-grass' mixture was also more expensive, with a long-term estimated cost of £765 per ha compared to £61 for the 'oversown-clover' mixture. The white clover (*T. repens*) in the 'oversown-clover' donor alleyways showed the best establishment of all cover crop species, whilst very few black (*M. lupulina*) medic plants established. The lucerne (*M. sativa*) and red clover (*T. pratense*) in the 'legume-grass' mixture also showed relatively low species cover despite the higher sowing rate of lucerne, this may have been due to competition with vigorous grasses, particularly cocksfoot (*D. glomerata*). This study shows that white clover is a suitable legume to use in alleyway cover crop mixtures, and whilst cocksfoot grass can produce a high volume of material it may outcompete other plants.

Despite all the advantages of cover crop mulches, the main barriers to their adoption are the need for specialised mowing machinery and the lack of knowledge on optimal species mixtures and management regimes. The success of cover crops will vary according to species mixtures, soil type and fertility, climate, establishment method, and management. The alleyway cover crops used in this study were producing 4.3 and 4.9 tons of dry mass per hectare annually for the 'oversown-clover' and 'legume-grass' treatments, respectively. These are at the lower end of expected clover-grass and lucerne yields, should their management be optimised, the yield of cuttings may be increased. Growing alleyway cover crops could prove to be a cost-effective and sustainable way of producing mulching material and adding nitrogen; negating transport costs, reducing mowing frequency, potentially reducing carbon emissions, and possibly allowing a reduction in herbicides and fertiliser applications (Mullinix and Granatstein, 2011; Patrick et al., 2004; Sirrine et al., 2008). There is a wide range of potential methods to grow and utilise alleyway cover crops and their cuttings. In established orchards, the existing alleyway vegetation could be used as is, or be oversown or replaced with a mixture of clovers and grasses. In new orchards, our results suggest a combination of methods: an initial layer of straw, or compost topped with straw, covering the weed strips, which is 'topped-up' with cuttings from the alleyway. If cover crops were sown during orchard establishment, only a minimal change of standard management would be required to produce mulch: mainly a reduction in mowing frequency and the adoption of side-discharging mowers.

Whilst the effects of traditional mulches have been well studied, and some of the longer-term benefits have been shown (Hogue and Neilsen, 1987; Merwin et al., 2003; Neilsen et al., 2003b), the use of alleyway cuttings is quite novel and still requires further research. For example, there is a need to further quantify the effects of cover crops and their cuttings on pest and disease dynamics and beneficial species such as pollinators and natural enemies of crop pests. Some studies have seen competition between cover crops and trees for water and nutrients (Du et al., 2015; TerAvest et al., 2011), but this will depend on the climate, cover crop type and management, and the width of the weed strip and there is evidence of improved soil fertility and production with cover cropping even in arid and semi-arid conditions (Ramos et al., 2011; Sánchez et al., 2007). The water-conserving ability of mulches may become very important in the near future, due to a combination of rising demand for water and more likely droughts in south-east England due to climate change (Allen et al., 2010; Vorosmarty, 2000). Mulches and cover crops may also play an important role in reducing the use of pesticides and synthetic fertilisers (Blanco-Canqui et al., 2015; Chalker-Scott, 2007; Jacometti et al., 2010), and potentially in sequestering carbon (Flessa et al., 2002; Poeplau and Don, 2015). This study demonstrates that mulching with traditional materials and mulching with cover crop cuttings can be a beneficial management practice that may enhance ecosystem services and improve soil health and sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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