Maximising the effectiveness of soil erosion reducing cover crops through plant trait analysis

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To the enlightened person a clod of soil and gold are the same.

Bhagavad Gita

Declaration

This thesis has not been submitted in support of an application for another degree at this or any other university. It is the result of my own work and includes nothing that is the outcome of work done in collaboration except where specifically indicated. Many of the ideas in this thesis were the product of discussion with my supervisors Professor Carly Stevens and Professor John Quinton both from Lancaster University.

This thesis word length is 45,334 and therefore does not exceed the permitted maximum.

Helena Ripley

November 2022

Statement of Authorship

This thesis has been prepared in the alternative thesis format as a set of four papers, chapters 2, 3, 4, and 5, with some intended for submission to peer-reviewed journals. The papers are presented in the format intended for submission minus references which can be found in a consolidated bibliography at the end of this thesis (References). These papers have multiple co-authors in addition to my direct supervisory team and each is acknowledged in respective relevant chapters. Chapters 1, and 6 are introductory, and discussion chapters, respectively, and are not intended for peer-reviewed publication.

Chapter 2

Helena Ripley[1], Carly Stevens[1] and John Quinton[1].

Plant trait analysis to determine species beneficial for use as soil erosion cover crops in Spanish orchards.

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Intended for publication in Journal of Arid Environments in combination with Chapter 4.

Chapter 3

Helena Ripley[1], Carly Stevens[1], John Quinton[1] and José Alfonso Gómez[2].

Impact of cover crops on soil and plant chemistry in an olive orchard in southern Spain.

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Chapter 4

Helena Ripley[1], Carly Stevens[1] and John Quinton[1].

A mesocosm experiment to assess the impact of different vegetation types as erosion control cover crop.

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Chapter 5

Helena Ripley[1], Carly Stevens[1], John Quinton[1], José Alfonso Gómez[2], Cristina McBride-Serrano[1,3] and Sofia Isabel Basto Mercado[4].

Farmer perceptions and management of soil erosion in tree crops in Spain.

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Statement of contribution

Prof Carly Stevens and Prof John Quinton contributed to the conception, design and execution of the experiments. They also provided feedback on draft chapters of this thesis.

Dr José Alfonso Gómez located a field site for Chapter 3, provided technical help with setting up the field site and collected samples when COVID-19 restricted access. He also checked the translation of the survey used in Chapter 5 and sent it to his contacts.

Dr Hongmei Chen, Emilee Severe, Dr Carmen Medina-Carmona and Cristina McBride-Serrano assisted with the maintenance and assessment of mesocosms in Chapter 4.

Dr Becky Whittle provided help with the experimental design of Chapter 5.

Cristina McBride-Serrano proofread the survey for Chapter 5, and interpreted the in-person interviews. Dr Sofia Isabel Basto Mercado transcribed and translated the recorded interviews for Chapter 5.

Dr Luke Rhodes-Leader, David Sudell and Dr Natalie Davies provided statistical and R support for Chapters 2,3 and 4.

Abstract

Soil erosion is a global issue, but particularly severe in Mediterranean hillside orchards due to the semi-arid climate, topography, climate change, and farming practices. Seasonal, annual cover crops successfully control soil erosion in orchards, this thesis used plant traits to determine effective cover species, as this not been previously considered.

Ten species, native to Spain and previously used as erosion-reducing cover crops, were assessed for above and below ground plant traits, infiltration and evapotranspiration. *Brachypodium distachyon*, *Bromus rubens*, *Medicago sativa* and *Silene vulgaris* showed the most promise for erosion control. In a field trial in Cordoba, Spain, these species revealed no nutrient competition between cover crops and tree crops but, the high carbon:nitrogen ratio and high nitrogen (N) content of the cover crops could increase soil N. A mesocosm trial was conducted using rainfall simulation to determine the runoff and soil loss from monocultures and a mix of *Brachypodium distachyon*, *Medicago sativa* and *Silene vulgaris*. All the vegetated plots significantly reduced soil loss compared to the bare plots, furthermore *M. sativa* had a dominant impact on the mix. Despite the knowledge that plants reduce soil loss, few tree crop farmers use vegetation cover. A survey and interviews were conducted to understand this practice, while most of the respondents used cover crops, they believed that lack of knowledge about sustainable soil management was a key barrier to the use of vegetation cover.

In conclusion, plant traits analysis provided vital information about the potential impact of species on soil erosion. However, the interactions of the species within mixes, and in the field, needs to be taken into consideration before widespread use. Any Mediterranean plant cover is better than none to prevent soil loss, which is a severe and urgent issue in Spain, therefore a clear transfer of information to farmers is vital.

Keywords: plant traits, soil erosion, hillside orchards, sustainable soil management

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List of acronyms and abbreviations

AGB – Above ground biomass

ARD – Average root diameter

ARL – Actual root length

BGB – Below ground biomass

BP – Before present

C - Carbon

MoE – Modulus of elasticity

N – Nitrogen

P – Phosphorus

RDM – Root dry matter

RV – Root volume

SLA – Specific leaf area

SRL – Specific root length

List of common and scientific names of species used

Alfalfa (*Medicago sativa*)

Annual ryegrass (*Lolium rigidum*)

Barrel medic (*Medicago truncatula*)

Bladder campion (*Silene vulgaris*)

Borage (*Borago officinalis*)

Burr medic (*Medicago polymorpha*)

False broom (*Brachypodium distachyon*)

Field marigold (*Calendula arvensis*)

Red broom (*Bromus rubens*)

White rocket (*Diplotaxis arvensis*)

1. Literature review

1.1 Tree crop production in the Mediterranean

1.1.1 Importance of tree crops

Great historical, cultural and economic importance is placed on tree crops in the Mediterranean (Durán Zuazo et al., 2006; Gómez et al., 2009a). Olive trees have grown wild in the Mediterranean for 4 to 8.3 million years, but their cultivation started with the formation of ancient civilizations around 6000 BP (Cecchini et al., 2018; Besnard et al., 2018). Citrus trees are not native to the Mediterranean: their domestication in Southeast Asia started several thousand years ago, followed by global distribution and cultivation throughout the Mediterranean by the 7th century (Wu et al., 2014; Ruas et al., 2017). Two staples of the Mediterranean diet olives, particularly olive oil, and oranges are not only culturally significant, but the trees have aesthetic value with many grown in cities (Cecchini et al., 2018). Farming tree crops (olive, citrus and stone fruit) in the Mediterranean is a significant source of income accounting for 3.6 M, 3.8 M and 12.2 M 1000 Int $ (currency used by FAO) in Italy, Greece and Spain, respectively, in 2020 (FAOSTAT, 2022). This large-scale production has resulted in significant changes to the land (Cantón et al., 2011). Human impact on the land in the Mediterranean has been clear for the last 4000 years; however, there have been many changes to land use and management over human history (García-Ruiz and Valero-Garcés, 1998; García-Ruiz, 2010).

1.1.2 Land use change

Over the last 300 years there has been continuous intensification of agriculture in Spain (Vanwalleghem et al., 2011). Amate et al. (2013) revealed that in 1750 2% of Montefrío (Andalucía) was olive groves, while this increased to nearly 3% by 1850, in 1900 it was back to 2% of the total area. Spanish production of olive oil increased 1.6 times compared to Italy between 1890s and 1910s, in this period Spain led global olive oil production (Ramón-Munoz, 2000). Intensified agriculture was particularly dramatic over the course of the 20th century due to technological advancement, population change and market forces (García-Ruiz, 2010). At the beginning of the 20th century the area of olive production once again expanded, to approximately 5% of total area. However the civil war

(1936-39) affected the export of olive products although the farmed area was maintained (Amate et al., 2013). Technological changes in tillage and herbicide use to remove spontaneous vegetation (i.e. weeds or native vegetation), growing between the crop trees, in addition to irrigation, were instrumental in the latter half of the 20th century (Vanwalleghem et al., 2011). Since the 1950s the olive area has again increased. In parts of Andalucía, for example, olive cultivation is responsible for almost all of the agricultural area and nearly 60% of Andalucía (Amate et al., 2013). Almond orchards have increased in area since the 1980s as they have been grown in hilly, previously abandoned areas in response to EU subsidies (García-Ruiz, 2010). Between 1982 and 2002 the recorded area of citrus cultivation in Valencia increased by 20% (Cerdà et al., 2021). However this was likely to be 40% due to non-registered citrus plantations (Cerdà et al., 2021).

Currently, Spain accounts for the greatest area (297,600 ha) of citrus cultivation in Europe, with 180,000 ha in Valencia producing over 70% of the national citrus yield (Cerdà et al., 2021; Mansour et al., 2021). Olive trees cover 2.5 million ha in Spain, 63% of which are in Andalucía (Amate et al., 2013; Calatrava et al., 2021). Andalucía also accounts for 30% of Spain's almond production and 28% of citrus cultivation by area (Calatrava et al., 2021).

1.1.3 Methods of cultivation

1.1.3.1 Traditional

Tree crops provide many services, such as firewood, grazing for livestock (silvopastoral farming) and materials for handicrafts, in addition to food, which often diversified and stabilised agricultural production at the start of crop tree cultivation (Wolpert et al., 2020; Cecchini et al., 2018). Traditional olive groves (Figure 1.1a) contain sparse and scattered olive trees, planted around shrubs, other crops or grazing land, with a low planting density of 17 – 50 trees ha^{-1} (Rallo et al., 2013; Amate et al., 2013). Traditional rainfed olive orchards, (Figure 1.1c), containing only olive trees and planted in rows, have been grown in the Mediterranean since the Roman period (Rallo et al., 2013). These have a planting density varying from 17 to over 300 trees ha^{-1} depending on the rainfall of the region (Rallo et al., 2013) The use of natural fertilisers such as manure, from animals and humans, and legumes has been practiced since early farming (McNeill and Winiwarter, 2004). From the 1820s to 1930s intensification of olive agriculture started, however between the 1930s and 1970s the impact of the Spanish civil war resulted in less olive production and the cultivation of wheat and barley grown in between olive trees, due to trade embargoes imposed by other countries as a result of the Franco regime (Wolpert et al., 2020; Vanwalleghem et al., 2011). The rate of soil erosion increased when the practice of growing cereal crops between tree crops ceased in the 1970s, and tillage and bare soil increased (Vanwalleghem et al., 2011). This is also when irrigation began in olive orchards. The planting density was the same as rainfed orchards (17 – > 300 trees ha^{-1}) but irrigation resulted in increased canopy volume and yield (Figure 1.1d) (Rallo et al., 2013). Canopies were pruned and bare soil was maintained to reduce water competition for the trees, which were also planted far apart to give a large area for the roots to search for water (Gómez, 2017). Since the 1990s herbicide use has replaced tillage in the removal of spontaneous vegetation in some farms, nevertheless, high rates of water based soil erosion are sustained, modelled at 43 to 124 t ha^{-1} yr^{-1} for olive groves in Andalucía (Vanwalleghem et al., 2011; García-Ruiz, 2010).

Prior to the 1980s orange orchards were flood irrigated and therefore primarily located on alluvial plains with water controlled by dams and irrigation ditches (Cerdà and Jurgensen, 2008). However, recently orange plantations have moved on to slopes and use drip irrigation, particularly in Eastern Spain, which was dominated by oak forests which were cleared for fuel and pasture (Cerdà and Jurgensen, 2008).

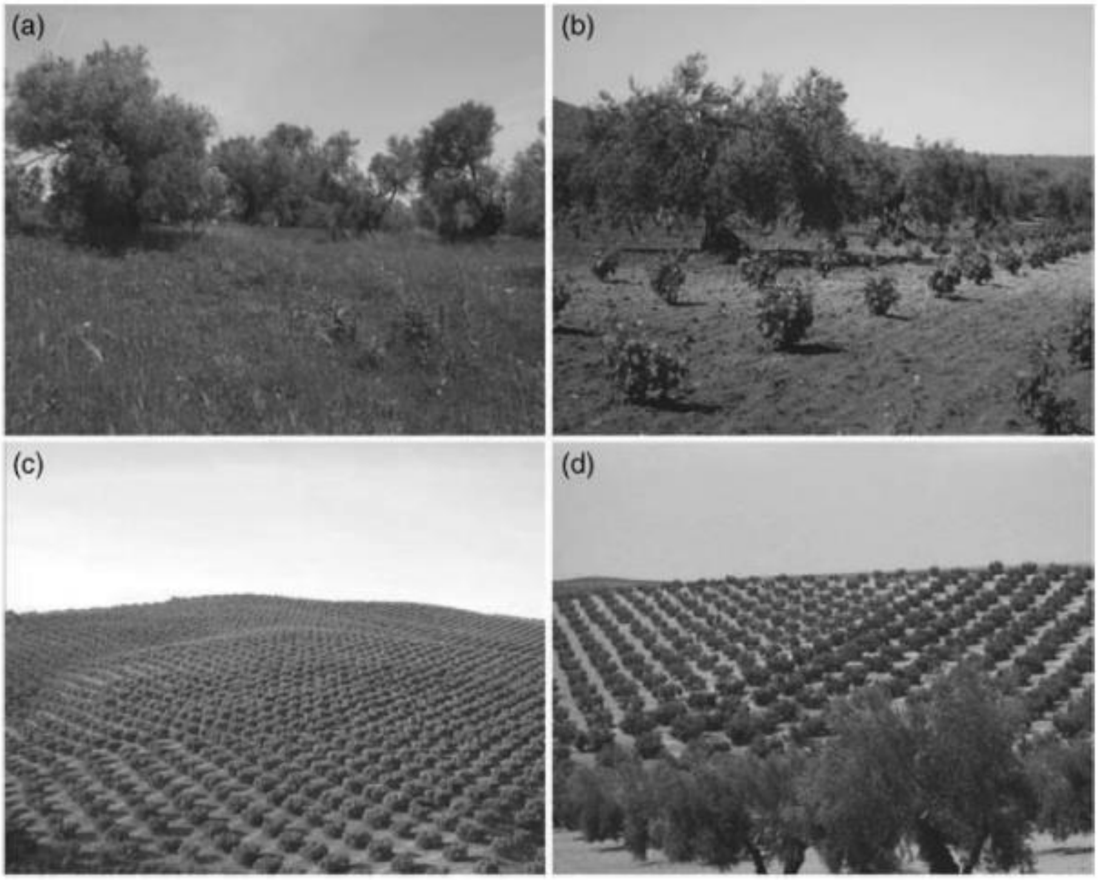


Figure 1.1: Photographs of traditional olive orchards from Rallo et al. (2013). (a) Grove. (b) Traditional associated orchard. (c) Traditional rainfed specialised orchard. (d) Traditional irrigated specialised orchards.

1.1.3.2 Intensive

The intensification of tree crops has been enabled through the use of chemical fertilisers, machinery advances and irrigation (Gómez, 2017; McNeill and Winiwarter, 2004). Intensive olive growing was introduced to Spain from Italy in the 1960s with high density planting of up to 800 trees ha^{-1} (Rallo et al., 2013). These orchards were designed to reduce labour and increase yield through cultivars that achieved a full crop by the 7th to 10th year (Rallo et al., 2013). However, the lifespan of the orchard was reduced to less than 40-50 years, a fraction of the hundreds of years a cultivated olive tree can live (Rallo et al., 2013; Vanwalleghem et al., 2011). This is a potential issue as older trees are more able to withstand competition for resources (Gucci et al., 2012). Rainfed intensive orchards are planted more sparsely (<100-250 trees ha^{-1}, 9 x 7 m to 7 x 6 m planting arrays) than irrigated intensive orchards (200-400 trees ha^{-1}, 8 x 6 m to 6 x 4 m planting arrays) due to the area needed by the rainfed trees to search for water (Gómez, 2017; Rallo et al., 2013).

Hedgerows were used to create very high density orchards of >1500 trees ha^{-1} in the 1990s due to the use of the vine straddle harvester (Rallo et al., 2013). Irrigated wide hedgerow orchards (Figure 1.2a and c) are planted at 7 x 3.5 m to 6 x 6 m, whereas the irrigated narrow hedgerow orchards are planted at 4 x 1.75 m to 3.5 x 1.35 m (Rallo et al., 2013). Furthermore, rainfed narrow hedgerow orchards are possible with larger distances between the rows (6-7 m) while along the rows the trees are still close together (1.5-2 m), decreasing the density to 800-1000 trees ha^{-1}. To maintain vehicle access to the crops for harvesting, pruning and treatment application, the crop trees need to be well spaced in rows, which are kept bare, increasing vulnerability to erosion (Vanwalleghem et al., 2017; García-Ruiz, 2010; Gómez et al., 2018). While the yields of crop trees have increased over the past few decades as a result of intensification, the process may have masked the effect of severe soil erosion on land productivity (Gómez et al., 2014).

Figure 1.2: Photographs of hedgerow plantation from Rallo et al. (2013). (a and c) Irrigated wide hedgerow or high density. (b and d) Irrigated narrow hedgerow or super high density or superintensive.

1.2 Soil erosion in Mediterranean orchard systems

1.2.1 Drivers and threats to agriculture

In the Mediterranean soil erosion is predominantly driven by water erosion, however, the soils are particularly vulnerable due to the topography and semi-arid climate which results in patchy vegetation and long dry periods followed by intense rainfall (Raya et al., 2006). The soils have high erodibility due to the lack of organic matter, (generally less than 2%) common textures are clay loams and sand loams of many soil types with Calcisol the most common (Silva et al., 2020; Ferreira et al., 2022; Garcia-Diaz et al., 2017).These factors decrease the formation of aggregates and increase erodibility (Pacheco et al., 2018). The annual rainfall in semi-arid areas is 200 to 600 mm, yet, most of the rainfall occurs in intense local events of over 30 mm hr^{-1} (Cantón et al., 2011; Abrisqueta et al., 2007). These intensive rainfall events predominantly take place in the autumn and winter, nevertheless, rain splash and runoff erosion can happen at any time of the year (Cantón et al., 2011; Keesstra et al., 2016). Rain splash erosion, caused by raindrop impact detaching soil particles, enables soil to be moved overland flow, while intensive rainfall can cause soil crusting preventing infiltration and causing runoff, this is not a major issue in Mediterranean orchards (SSSA, 2008; Zuazo et al., 2009).

Soil erosion is a major global problem with up to 120, 000 Mt of soil estimated to be eroded from agricultural land annually (Doetterl et al., 2012). Within Spain erosion rates are on average 3.2 t ha^{-1} yr^{-1}, whereas soil formation is typically less than 0.2 mm per year, and tolerable soil erosion in Spanish olive orchards are between 10-12 t ha^{-1} $year^{-1}$ (Gómez et al., 2014; Jones et al., 2010). However, erosion in hillside orchards is 50 t ha^{-1} yr^{-1}, this is twice the estimated average global erosion from agricultural land in 2010 of 25 t ha^{-1} (Taguas and Gómez, 2015; Doetterl et al., 2012; World Bank, 2023). Consequently, a decrease in yield due to soil loss is clear in the Mediterranean (Keesstra et al., 2016; Segovia et al., 2017; Benlhabib et al., 2014). This loss in yield is due to a reduction in the water holding capacity of the shallower soils. Therefore, the amount of water available for the crop trees is reduced and the yield is affected (Gómez et al., 2014). In Spain alone, there has been a loss of 29 to 40% of the total soil depth of agricultural land compared to non-farmed land (Vanwalleghem et al., 2011). Subsequently, the financial impact is estimated to be over €1bn per year (Wuepper, 2020). The impact of severe soil erosion on agriculture, and the effect of agriculture, on erosion, is clear, therefore, mitigation and adaptation techniques are required from growers to increase the sustainability of tree crop cultivation (Ruiz-Colmenero et al., 2013; Segovia et al., 2017). Although farmers are now required to cover bare soil on slopes greater than 10 % (Taguas and Gómez, 2015), comprehensive research into the traits of plants suitable as cover crops has not been previously carried out.

Runoff erosion is responsible for forming rills and gullies as it transports soil from fields to rivers, this movement of sediment and nutrients causes siltation and pollution of water bodies (de Graaff et al., 2010; Bronick and Lal, 2005).

This pollution is costly to remediate; moreover, the loss of soil from agricultural land is a great ecological and financial problem (Segovia et al., 2017). Calatrava et al. (2021) identified that water pollution was considered a graver issue than polluting emissions from agrochemicals used on soil by almond growers in Murcia and olive farmers in Andalusia. Whereas, citrus growers in Murcia judged both types of pollution to be equally serious. Over use of fertilisers and pesticides was thought to be a more pressing problem than the resulting pollution by all of the farmers (Calatrava et al., 2021). Leaching, particularly where N-fertiliser is overused, can be 50-150 kg ha^{-1} yr^{-1}, which not only affects surface water but also groundwater where increased levels of N have been noted in conjunction with citrus orchards, particularly under sandy loam soils (Kurtzman et al., 2013; Calatrava et al., 2021). While citrus trees have a higher demand for N-fertiliser than almond trees, any use of fertiliser in almond orchards causes pollution (Calatrava et al., 2021). However, an increase in ground cover, and optimisation of water and fertiliser, can decrease pollution and increase yield (Gonzalez-Sanchez et al., 2015; Qin et al., 2016).

Increases in water pollution and soil erosion are partially due to technological advancement, driven by population change and subsidies from the European Common Agricultural Policy (CAP) (García-Ruiz, 2010; Oñate and Peco, 2005) . While Spanish and European subsidies profess to improve soil and water sustainability, there are divergences between the practices supported by these subsidies and those considered most ecologically sound (Cantón et al., 2011). For example, the CAP which subsidised almond cultivation on fragile slopes did not support the adoption of the best erosion control practice (Rojo Serrano et al., 2002). The previous iteration of CAP from 2014-2020 was lauded as greener than previous versions, however, there was a lack of financial support for small farms which resulted in a reduction of biodiversity and soil quality (Pe'Er et al., 2014). A lack of financial support was also noted by Taguas and Goméz (2015) in the context of farming on steep slopes as erosion control incentives were only in place for slopes over 10% and ploughing was only banned for those greater than 15%. Resilience, of farmers' incomes and ecology, and to climate change and geopolitical tension, is a key value of the CAP 2020 reform, which includes the Biodiversity and Farm to Fork strategies, however the framing of the term is ambiguous and the areas of resilience focus do not all align (European Commission, 2020; Buitenhuis et al., 2022). Due to the rapid soil erosion, the European Common Agricultural Policy (CAP) moved, in the early 21st century, towards promoting the use of mulch and plant cover to control soil loss (Bednar-Fridl et al., 2022; Taguas and Gómez, 2015; Vanwalleghem et al., 2011). Unfortunately, high rates of erosion are still occurring.

1.3 Approaches to soil conservation in Mediterranean orchard systems

1.3.1 Terraces

Due to the long history of agriculture and soil erosion, many agricultural developments have been used to control soil loss. Specifically, terraces, contour tillage, and cover crops: the historical land use changes are explored further in section 1.2 (McNeill and Winiwarter, 2004). Terrace building as a technique to reduce soil erosion has been in practice for over 4000 years, it remains an effective method which is still widely used in hillside orchards (Brevik and Hartemink, 2010; Vanwalleghem et al., 2017). The soil stabilisation offered by terraces, provided that they are well positioned and maintained, has resulted in the long historical and current use of terraces in spite of the high level of labour required (McNeill and Winiwarter, 2004).

1.3.2 Tillage

Tillage is commonly mouldboard or harrow ploughing in the Mediterranean (Vanwalleghem et al., 2011). This reduces runoff by increasing surface roughness and breaking up soil crusts, forming surface depression storage and increasing infiltration (Ruiz-Colmenero et al., 2013; Moore et al., 2008). The direction of tillage is important, as tilling perpendicular to the contours encourages runoff and erosion, whereas tillage along the contour provides many small barriers to runoff (Vanwalleghem et al., 2017). Conventional tillage harms the soil through destruction of soil structure and leaving smaller aggregates vulnerable to movement (tillage erosion) (Brevik and Hartemink, 2010). Therefore, reduced tillage or no-till has been in use since the early 20th century (McNeill and Winiwarter, 2004). While not tilling decreases tillage erosion it does result in increased water erosion due to the lack of surface roughness provided by tillage (Vanwalleghem et al., 2017). Another use of tillage in Mediterranean orchards is to remove spontaneous vegetation from between tree crop rows which could compete with the tree crops for water and nutrients (Keesstra et al., 2016).However, with the increase in no-till methods, herbicides have been used, and in many cases over used, to control plant growth therefore resulting in bare soil vulnerable to erosion (Ruiz-Colmenero et al., 2013). Compared to tillage, herbicide use as a form of vegetation removal causes reduces soil pores formation and prevents infiltration (Zuazo et al., 2009). On the other hand seasonal plant cover, allowed to develop for a few months before being killed, increases pores and provides protection for the otherwise bare soil (Angers and Caron, 1998).

1.3.3 Cover crops

Cover crops are an effective means of erosion control due to the interception of raindrops and subsequent decrease in splash erosion, and the increase in infiltration promoted by plants (Gyssels et al., 2005; Palese et al., 2014). Plant cover to control soil erosion in orchards has many iterations, from vegetated barriers to an increased consideration of soil coverage resulting in the use of cover crops and plant residue (de Graaff et al., 2010; Moore et al., 2008). Soil erosion reduction under cover crops correlates with the amount of ground covered by the plants (Cantón et al., 2011; Abu-Zreig et al., 2003). Consequently, over 40% cover is deemed necessary on sloping ground (Zuazo and Pleguezuelo, 2008b), while less than 15% cover is ineffective and increasing naturally low cover is costly as irrigation may be required (Rogers and Schumm, 1991). Providing sufficient ground cover is achieved, soil retention benefits are noticeable quickly. There are also longer-term benefits to the soil such as an increase in soil quality in terms of increased nutrients, organic matter, improved soil structure and ground water recharge (Keesstra et al., 2016; Zuazo and Pleguezuelo, 2008b). The short- and long-term effectiveness of cover crops depends on the species used, with monocultures being less effective than mixes due to a lack of diversity in both above and below ground plant traits (Zhu et al., 2015; Bronick and Lal, 2005).

1.4 Cover crops in the Mediterranean context

1.4.1 Approaches to their use

Spontaneous vegetation has long been removed from Mediterranean orchards, as mentioned in section 1.3.2. While there has been some increase in cover crop use, there is a lot of variation in the reported number of farmers using vegetation. In olives 6% (Sastre et al., 2017), 50% (Calatrava Leyva et al., 2007) and 63% (Gómez et al., 2021) of 119, 223 and 146 surveyed Spanish farmers, respectively, used cover crops. Furthermore, a study of 139 citrus farmers by Cerdà et al. (2018) revealed 10% of the growers used cover crops, indicating a lower uptake than by olive farmers. Cover crops can be spontaneous or planted, farmers may mix the type of plant cover due to pest or weed control, or the high nutrient or water use of the spontaneous vegetation (Gómez et al., 2021; Novara et al., 2021). The tree crops growing in Spain are adapted to the climate and low water availability. Nevertheless, increased demands on a finite supply of water negatively affect the quantity and quality of crop yields (García-Ruiz et al., 2011). Gucci et al. (2012) noted a 65% decrease in olive fruit yield from crops under a permanent natural cover, while a slight increase in soil water conductivity and storage, offset the effects of rainfall variability in long-term cover or no-till treatments (Basche and DeLonge, 2017; Araya et al., 2022). In seasonal trials, where the vegetative cover was killed in spring (Figure 1.3), a positive impact of cover crops was noted, with greater soil moisture observed under plant cover than no-till plots by Zuazo et al. (2009) and Keesstra et al., (2016).

Sastre et al. (2020) observed a significant olive yield decrease under a permanent false broom (*Brachypodium distachyon)*cover due to N competition. However this was not noted in permanent spontaneous vegetation or annual bitter vetch (*Vicia ervilia)* (Sastre et al., 2020). Vegetation cover can stabilise soil nutrients due to the reduction in erosion of nutrient containing soil (Jang et al., 2021; Lee et al., 2014; Gómez et al., 2009a). Leguminous cover crops increase the N content of the soil due to the biological N fixation resulting from a symbiotic interaction with rhizobial bacteria, delivering enough N to tree crops to negate the use of mineral N fertilisers (Ovalle et al., 2010; Snoeck et al., 2000; Peoples et al., 1995). Soil erosion happens most frequently in the autumn and winter in semi-arid areas. Therefore, fast growing species that will establish in the autumn and be killed, or die off, in the spring are ideal (Figure 1.3) as most of the competition discussed above is associated with permanent cover (Gómez, 2005; Raya et al., 2006). Comparison of the reduction of soil loss under cover crops with damaging herbicide and tillage practices has been important to persuade decision makers of the value of plant cover. Consequently, a range of annual species have been investigated for erosion control suitability in orange (e.g. Mauro et al., 2015), apricot (e.g. Keesstra et al., 2016) and olive (e.g. Palese et al., 2014) crops.

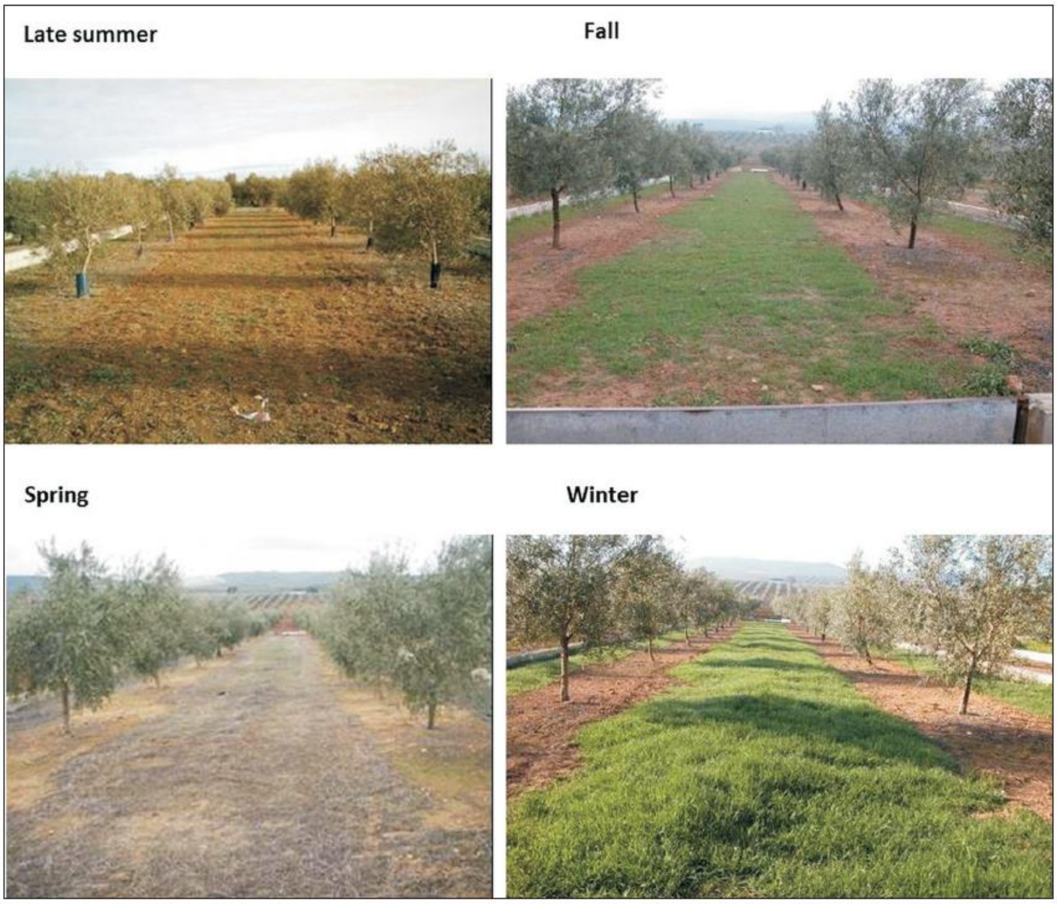


Figure 1.3: Seasonal cover in an orchard using plant cover only through the autumn and winter. Photograph from Gómez et al. (2017).

1.4.2 Species

The need for fast growing annual species as inter-row cover crops means that grasses, forbs and legumes are the most commonly used plant functional types

(Table 1.1). Furthermore, these functional types provide other benefits to the orchards such as attraction of pollinators and soil conditioning (Sastre et al., 2017; Francia Martínez et al., 2006; Gómez et al., 2018). Another advantage is that fast growing species are associated with more positive below ground plant soil feedbacks than slow growing species (Baxendale et al., 2014). Fast-growing species may have general benefits for soil health but not all species are effective at controlling soil erosion. Many studies have been carried out in Spain to investigate this. Table 1.1 describes eight studies carried out in almond, apricot, olive and citrus orchards in Spain between 2006 and 2018. Both comparisons of different vegetation treatments (Raya et al., 2006; Durán Zuazo et al., 2006) and contrasts of vegetation with tillage (e.g. Sastre et al., 2017) are common, moreover, vegetation reduced soil loss when compared to any type of tillage in all of the studies in Table 1.1.

Table 1.1: Studies conducted in Spanish orchards, comparing vegetation treatments with other plant cover							
Study	Location of study	Tree crop	Treatments and associated soil loss	Soil type	Mean annual rainfall (mm/yr)	Maximum cover achieved (%)	Time to cover (days)
Raya et al. (2006)	Sierra Nevada, Granada, SE Spain	Almonds (*Prunus amygdalus*).	Three treatments: Thyme (*Thymus baeticus*) (87.5% less erosion than lentil plots) , barley (*Horedum vulgare*) (50.8% of the soil erosion from lentil plots) and lentils (*Lens esculenta*) (soil erosion mean 4449.3 kg ha^{-1} y^{-1}) .	Loamy texture.	282	Not reported.	Not reported.
Keesstra et al. (2016)	South of Valencia E Spain	Apricot (*Prunus armeniaca*).	Three treatments: herbicide treatment (soil	Soil is a Typic Xerorthent, loamy texture.	620	Average vegetative cover in winter is 87%,	Not reported.

			erosion 0.91 t ha^{-1} h^{-1}); tilled fields (56% of erosion of herbicide treatment); vegetation cover and pruning residuals (2% of the soil erosion from herbicide plots).			during summer 56%.	
Francia Martinez et al. (2006)	Sierra Nevada mountains, Granada, SE Spain	Olive (*Olea europaea*).	Three treatments: no-till with barley strips (*Hordeum vulgare*) (8.2% of soil eroded from no-till without plant strips); conventional tillage (22% of the soil erosion from no-till	Typical Xerorthent, loamy soil texture	365.2	Not reported.	Not reported.

			without plant strips); and no-till without plant strips (25.6 t ha^{-1} yr^{-1}).				
Gómez et al. (2009b)	West of Seville, SW Spain	Olive (*Olea europaea*).	Two treatments: conventional tillage (2.9 t ha^{-1} yr^{-1}); cover crop of *Lolium rigidum* or *multiflorum* depending on seed availability (72% less soil loss than conventional tillage plots).	Petrocalcic Palexeralf soil series, sandy loam texture.	534	Not reported.	A few weeks: plots seeded in autumn of 2003, runoff and sediment collection started in Sept 2003.
Zuazo et al. (2009)	Granada, SE Spain	Olive (*Olea europaea*).	Three treatments: non-till with barley (*Horedum vulgare*) strips (	Typic Xerorthent, loamy texture.	382.9	Not reported.	Not reported.

			produced 29% of the soil erosion of the no-till with no plants plots) ; non-till with native vegetation strips (59% less soil loss than no-till without plant strips); and non-till with no plant strips (soil loss of 17.3 t ha^{-1} yr^{-1}).				
Sastre et al. (2017)	Madrid, Central Spain	Olive (*Olea europaea*).	Four treatments: tillage (soil loss of 6.81 t ha^{-1} yr^{-1}); two annual covers, barley (*Hordeum vulgare L.)* (soi loss – 40% of that from tillage	*Haplic Gypsisol* with a xeric moisture regime. Silty soil.	390	Not reported.	Over 40% for false broom (*B. distachyon*); around 20% for the annual covers.

			plots) and legume (*Onobrychis viciifolia* Scop.) (soil erosion 59% of that produced in the tillage plots); and a permanent cover of false broom (*Brachypodium distachyon)* (soil loss 80% less than from tillage plots).				
Gómez et al. (2018)	Benacazon, Seville, S Spain	Olive (*Olea europaea*).	Three treatments: traditional tillage (soil loss of 46.7 t ha^{-1} yr^{-1}); annual ryegrass (*Lolium multiflorum)* (86% less soil loss than	Petrocalcic Palexeralf subgroup with sandy loam texture.	534	Well over 30%.	At least a few weeks.

			from the tilled plots); and a mixed seed cover crop (83% less soil loss than tilled plots).				
Cerdà et al., (2018)	Valencia, Eastern Spain	Citrus (Navel lane late variety	Two treatments: catch crops (*Vicia sativa* L. and *Avena sativa* L.) (reduced soil loss by 2% compared to second treatment) and weeds (*Parietaria officianalis, Urtica dioica, Malva sp., Diplotaxis erucoides, Amarantus spp., Chenopodium spp., Cyperus*	Xerorthent, loam	550	56.6 ± 7.1% for weed plots and 55.2 ± 15.2% for the catch crops.	Not reported.

			rotundus, *Portulaca oleracea*, *Setaria viridis*, *Setaria glauca*, and *Echinocloa colona*) (soil loss of 11.97 g m^2 h^{-1}).				

1.4.3 Traits

Using vegetation cover in an orchard requires careful consideration of how the cover crops will interact with the soil and the crop trees, plant trait analysis can therefore help to determine how individual species may behave (De Baets et al., 2009). Plant traits are a means of classifying plants outside of species taxonomies, linking plants that otherwise may not be considered to have similar properties. Such as species with dissimilar functional groups but a similar trait e.g. a tap root found in wild carrot (*Daucus carota*), a forb, and alfalfa (*Medicago sativa*), a legume (Lavorel and Garnier, 2002). Multiple plant traits are beneficial for the control of soil erosion and runoff formation, as they prevent the detachment of soil via splash erosion, trap sediment and reduce rill and gully formation, and promote infiltration (Figure 1.4). Figure 1.4 demonstrates that both above and below ground traits are important and illustrates that different species provide different benefits. For example, a small root diameter is ideal for forming a mat to prevent soil detachment if the roots grow near the soil surface. Whereas the large root diameter of a tap root is ideal for anchoring the soil and biodrilling to alleviate compaction and create macropores for other roots to follow (Bardgett et al., 2014; Freschet et al., 2017).

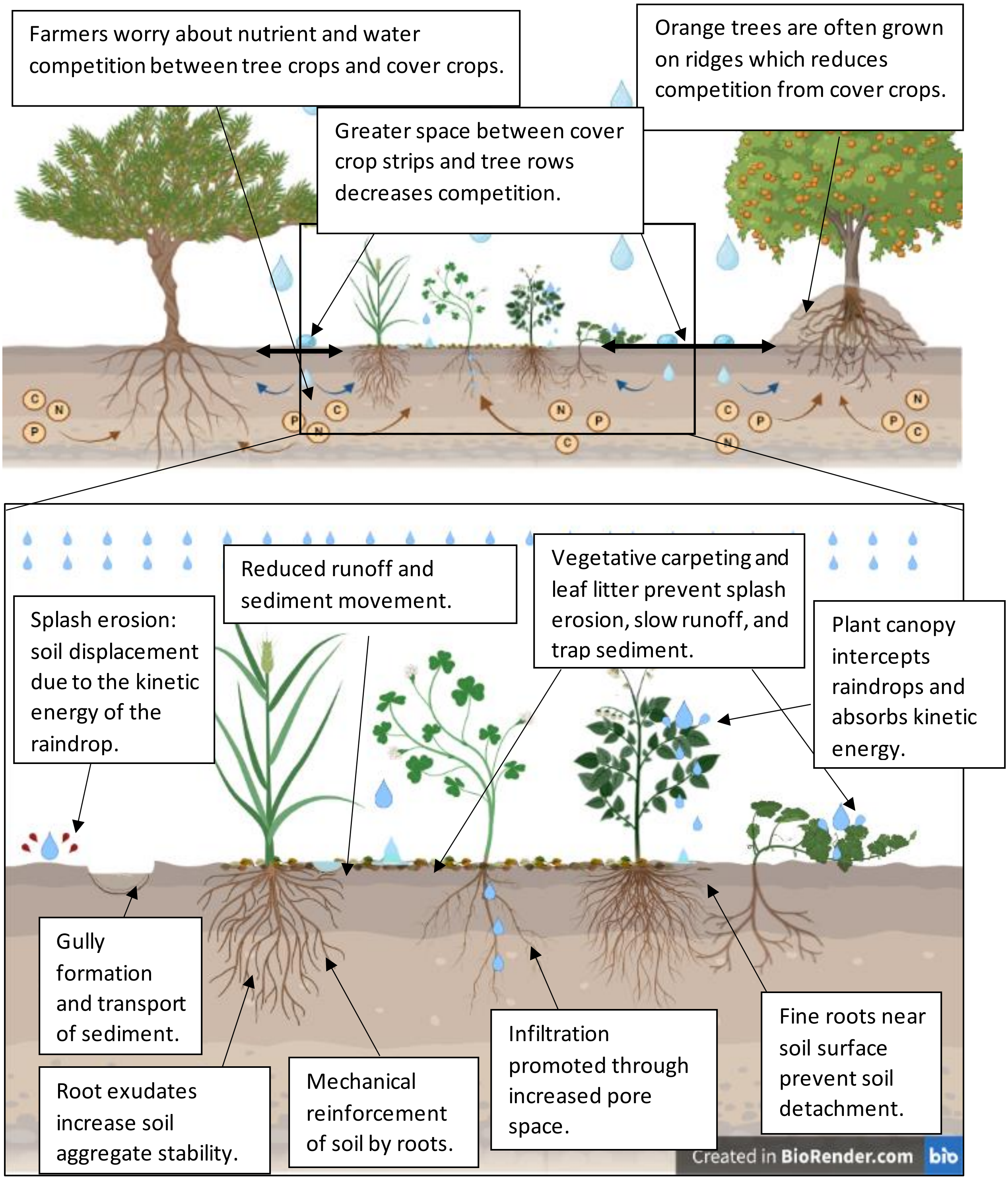


Figure 1.4: An annotated diagram of the impacts of cover crops on tree crops, and above and below ground plant traits on soil erosion and runoff.

Above ground control of soil erosion by plants is largely due to the prevention of splash erosion. On bare ground the kinetic energy (KE) of the raindrop is transferred to the soil matrix, causing aggregates to break up (Morgan, 2005). This increases the ease with which soil can be transported by water (Pacheco et al., 2018). Raindrops are intercepted by leaves and stems which absorb the KE and decrease the raindrop size prior to its contact with the soil surface (Bochet et al., 2006). There is no erosive impact of leaf drips from cover crops as this is only an issue for plants over 2 m (Morgan, 2005). Furthermore, leaves and stems dissipate the energy of wind, rainfall and runoff (Morgan, 2005; Gómez, 2017). The resilience of stems to bending under intense rainfall or under overland flow is measured by stem elasticity, this is an important consideration when choosing species needed to withstand extreme rainfall events (Table 1.2) (Dabney et al., 1996). The percentage of ground cover provided by vegetation correlates with the effectiveness of a cover crop to reduce soil loss (Table 1.2) (Zuazo and Pleguezuelo, 2008b; Rogers and Schumm, 1991). Furthermore, the carpeting effect of some plant species prevents splash erosion and also slows overland flow and traps sediment (Raya et al., 2006). Table 1.2 outlines studies that have found vegetative carpeting to be effective at reducing splash erosion both as a single species and as a mixture - with leaf litter caught under the vegetation enhancing the effect (Raya et al., 2006; Zuazo et al., 2009). On the other hand, high shoot density slows overland flow, encouraging infiltration and the deposition of sediment (Table 1.2) (Gyssels and Poesen, 2003; De Baets et al., 2008).

Reduction in runoff volume through infiltration is also promoted by the increase of total pore space and pore space connectivity through soil sealing remediation and the creation of pores due to root growth and decay (Table 1.2) (Loades et al., 2010; Ruiz-Colmenero et al., 2013). Another below ground benefit is the increase of stable soil aggregates due to the binding properties of root exudates, and the binding materials (including 5-enol-pyruvyl-shikimate-3-phosphate synthase) of the micro-organisms they attract (Gyssels and Poesen, 2003; Basche and DeLonge, 2017; Levy-Booth et al., 2009). Furthermore, roots provide mechanical reinforcement of soil as roots have a relatively high tensile strength, reinforcing the soil’s low tensile strength (Gyssels and Poesen, 2003; De Baets et al., 2006; Morgan, 2005).

The impact of the selected cover crop species on soil water availablity is an important consideration for plants used in Mediterranean orchards. There are different factors to consider including evapotranspiration, soil evaporation, infiltration and ground water recharge (Gómez et al., 2018; Francia Martínez et al., 2006; Sastre et al., 2016). Evapotranspiration accounts for the plant's use of water, which varies between species, and draws from soil water, however, plants also provide shading and reduce the evaporation of dew, which allows for soil water to recharge faster than under bare soil (Basche and DeLonge, 2017). Ground water recharge is also promoted by plant growth by increasing infiltration compared to sealed soils (Gómez, 2017). Moreover, roots can increase pore space connectivity which enables the movement of water through the soil (Ruiz-Colmenero et al., 2013).

Table 1.2: An overview of erosion controlling plant traits, articles that examined these traits and how they were measured.

Erosion related plant trait or soil conditioning by plant	Examined by	Focus of the study (not all are erosion focused as this is an understudied area)	Methods used to identify plant trait
Plant height	Baxendale et al. (2014)	Plant-soil feedbacks in fast- and slow-growing plant communities.	Followed the methods described by Cornelissen et al. (2003) and Perez-Harguindeguy et al. (2013), these are outlined in Chapter 2.
	Bochet et al. (2006)	Influence of plant morphology and rainfall intensity on soil loss and runoff.	Method not described.
	De Baets et al. (2007a)	Erosion reducing potential of root characteristics.	Used a ruler to measure height.
	Quinton et al. (1997)	Influence of plant species and properties on runoff and soil erosion.	Method not described.
Stem elasticity	Dabney et al. (1996)	Elastic limit of grass hedge stems used to control gully erosion.	Measuring the dimension of stems to calculate the moment of inertia prior to suspending weights from the stem to record the elastic limit. More information in Chapter 2.

	De Baets et al. (2009)	Evaluating plant traits to controlling rill and gully erosion.	Calculated the modulus of elasticity using a three point bending test following Goodman et al. (2001).
Specific leaf area	Baxendale et al. (2014)	Plant-soil feedbacks in fast- and slow-growing plant communities.	Followed the methods described by Cornelissen et al. (2003) and Perez-Harguindeguy et al. (2013).
Above ground biomass	Baxendale et al. (2014)	Plant-soil feedbacks in fast- and slow-growing plant communities.	Plant biomass was dried at 60^{o}C for one week.
Canopy cover	Bochet et al. (2006)	Influence of plant morphology and rainfall intensity on soil loss and runoff.	Visual estimation.
	Quinton et al. (1997)	Influence of plant species and properties on runoff and soil erosion.	Method not described.
	Rogers and Schumm (1991)	Effect of sparse vegetation cover on erosion.	Placing of grass plugs to achieve desired cover.
Vegetative carpet	Zuazo et al. (2009)	Impacts of plant strips on soil water dynamics.	Method not described.

Leaf litter	Bochet et al. (2006)	Influence of plant morphology and rainfall intensity on soil loss and runoff.	Visual estimation.
	Quinton et al. (1997)	Influence of plant species and properties on runoff and soil erosion.	Method not described.
	Zuazo et al. (2009)	Impacts of plant strips on soil water dynamics.	Method not described.
Root diameter	Baxendale et al. (2014)	Plant-soil feedbacks in fast- and slow-growing plant communities.	Conducted root diameter analysis on washed roots using WinRhizo root analysis software and an Epson flatbed scanner.
	De Baets et al. (2008)	Contribution of root tensile strength and distribution to soil shear strength.	Roots were spread on a sheet and digitally photographed to determine the diameter.
	De Baets et al. (2007a)	Erosion reducing potential of root characteristics.	Method not described.
	Freschet et al. (2017)	Plant functional types driving fine-root trait variation.	Analysed results from a database so did not report the methods used.
Root length	Baxendale et al. (2014)	Plant-soil feedbacks in fast- and slow-growing plant communities.	Conducted root diameter analysis on washed roots using WinRhizo root analysis software and an Epson flatbed scanner.

	De Bates et al. (2007a)	Erosion reducing potential of root characteristics.	Took digital photographs of roots and analysed total root length using Mapinfo Professional 6.0.
	De Bates et al. (2007b)	Root architecture impact on erosion-reducing potential of roots.	Roots were washed and dried, the length of a unit of dry mass was measure manually and total root length was calculated.
	De Baets et al. (2008)	Contribution of root tensile strength and distribution to soil shear strength.	Roots were spread on a sheet and digitally photographed to determine the diameter.
	Freschet et al. (2017)	Plant functional types driving fine-root trait variation.	Analysed results from a database so did not report the methods used.
Mechanical reinforcement of soil	De Baets et al. (2008)	Contribution of root tensile strength and distribution to soil shear strength.	Root tensile strength was analysed on washed roots using a universal tensile and compression test machine.
Increased pore space	Zuazo et al. (2009)	Impacts of plant strips on soil water dynamics.	Soil water content to determine infiltration was measured using Sentek EnviroSCAN multisensor capacitance probes at different depths.

Increased soil aggregate stability	Baumert et al. (2018)	Influence of root exudation on soil aggregation.	Used the wet sieving method to separate out different size classes of water stable soil aggregates.

1.5 Barriers to adoption of cover crops

Water competition with tree crops and the impact on yield is a source of concern for farmers when implementing changes to land management. However, section 1.4.3 described the difference in water use between species and that use of cover crops with specific plant traits can result in an increase in soil water (Basche and DeLonge, 2017; Ruiz-Colmenero et al., 2013). At present both rainfed and irrigated crop trees are the norm in Spanish orchards, with many trees irrigated for the first few years as they establish and rainfed thereafter, concerns regarding water competition therefore are more common when trees are solely rainfed (Gómez, 2017).

In the European Union (EU) 24% of land has unsustainable water erosion, within Spain risk of severe to very severe erosion and medium soil loss affects 13% and 34% of land, respectively (EC, 2020; Panagos et al., 2020; Repullo-Ruibérriz de Torres et al., 2018). Soil erosion has decreased in 20 EU member states since 2010, but in Spain, Italy and Greece it has increased, this is in part due to the lack of mitigation action (Figure 1.5) (Panagos et al., 2020; Wuepper, 2020). Within hillside orchards in Andalucía erosion occurs in at a rate of 50 t ha^{-1} yr^{-1}, much higher than the average Spanish erosion of 3.2 t ha^{-1} yr^{-1} (Taguas and Gómez, 2015; Gómez et al., 2014). As discussed in Section 1.4 cover crops have great potential for controlling erosion but the slow uptake of cover crops by Spanish farmers (used by 6% (Sastre et al., 2017) to 63% (Gómez et al., 2021) of olive farmers, and 10% (Cerdà et al., 2018) of citrus growers) is partially due to a lack of communication from the researchers to the agricultural and political stakeholders. Furthermore, the use of vegetative cover in orchards requires some cultural shifts to become widely acceptable by Spanish farmers (Cerdà and Rodrigo-Comino, 2021; Hondebrink et al., 2017). The education of farmers and their access to the training sessions is a key factor in their awareness of different soil management techniques (Sousa et al., 2020). Keesstra et al. (2019) found the cultural perception of farm tidiness is a barrier to the use of cover crops; tree crop rows with vegetation growing between them were considered to be “unclean”. In fact, 94% of the vineyard farmers surveyed by Cerdá and Rodrigo-Comino (2021) thought that the use of cover crops was “dirty” management.

Another motivational issue for farmers is the lack of subsidies and funding available to switch to using cover crops to manage soil erosion in hillside orchards (Keesstra et al., 2019). While use of spontaneous vegetation is relatively low cost, if planted cover crops are required the initial costs may exceed those of standard tillage or herbicide (Marques et al., 2015). In addition to the water and nutrient concerns discussed in sections 1.5.1 and 1.5.2, cost of cover crops is another worry for farmers. Planted vegetation cover requires seeding, maintenance and, sometimes, removal which can make them expensive (Taguas and Gómez, 2015). The cost faced by individual farms when changing soil management technique varies immensely. For instance for a large farm (> 30 ha) to start mulching branches, to reduce erosion, rather than burning them will cost an additional 10%, however a small farm (< 10 ha) could face an increase of 80% of their running costs (Cerdà and Rodrigo-Comino, 2021).

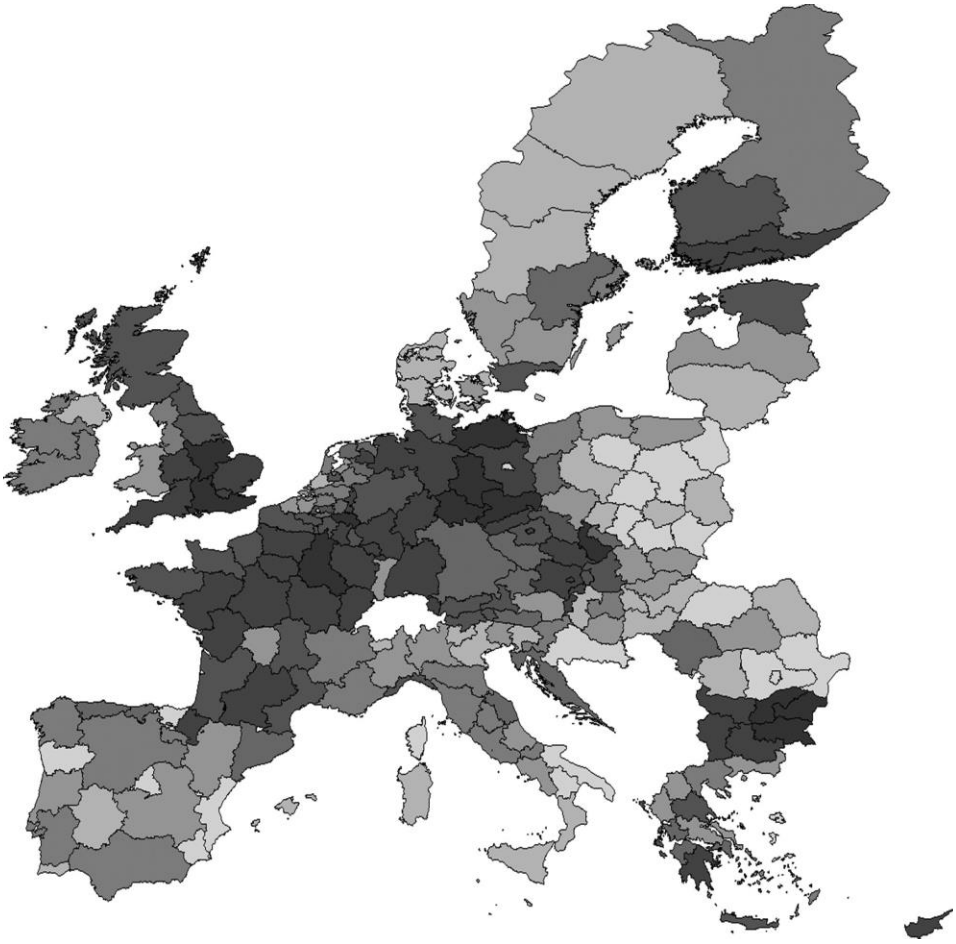


Figure 1.5: Map indicating the erosion mitigation in Europe, the darker areas have more mitigation than the lighter areas. Here mitigation is defined as the difference between current erosion rate and the rate of soil loss if there was no erosion management. Figure from Wuepper (2020).

This disparity in costs is not considered in the subsidies available, leaving farmers only willing to pay the additional cost of cover crops if they will recoup it in their profits or if erosion is causing disruption to their operations (Cerdà and Rodrigo-Comino, 2021; Marques et al., 2015).

Salazar-Ordóñez (2011), reported that citizens in southern Spain found agriculture, economy, environment and society equally important, despite the prioritisation of economic factors by CAP, demonstrating the holistic requirements of sustainability. This is supported by Wuepper (2020) who observed that EU wide agricultural policies cannot work due to the importance of culture at a national level. Due to the barriers to the use of cover crops faced by Spanish farmers, there is increased need for stricter policies, monitoring, education and funding (Wuepper, 2020; Cerdà and Rodrigo-Comino, 2021; Sousa et al., 2020).

1.6 Conclusions

Soil erosion reduces the productivity of agricultural land and causes pollution of watercourses; furthermore, soil loss is increasing due to the impacts of climate change (Gómez et al., 2018; Segovia et al., 2017). High rates of soil erosion in hillside orchards, combined with the concerns of farmers on the impacts of water and nutrient competition on their crop yield, indicates the need for seasonal cover crops (Keesstra et al., 2016; Gucci et al., 2012). These would control soil erosion during the months with the heaviest rainfall, and therefore the most soil loss, but would die off or be killed before the dry months when the risks of water competition are highest (Gómez et al., 2018; Araya et al., 2022).

While the benefits of plant cover to control soil erosion have long been understood (Morgan, 2005), there has been little research into the use of plant traits to identify effective seasonal cover crops for use with tree crops. Most of the plant trait research that has been conducted with erosion in mind has been in abandoned farmland (De Baets et al., 2009; De Baets et al., 2007a; De Baets et al., 2008; Quinton et al., 1997) or non-agricultural land (Bochet et al., 2006; De Baets et al., 2008), therefore interactions with tree crops have not been a consideration and perennial plants were used. Where cover crops have been trialled with tree crops, the traits of the planted or spontaneous vegetation have not been considered (Table 1.1). Furthermore, despite the academic research into controlling erosion in Mediterranean orchards, there has been a slow change in farming practice and only a small number of the researchers conducting field trials have attempted to understand this (Sastre et al., 2017; Gómez et al., 2021; Cerdà et al., 2018; Calatrava Leyva et al., 2007).

1.7 Research gaps

The use of cover crops to control soil erosion in the Mediterranean is widely studied (Table 1.1). However, plant traits have not been extensively used in these studies (Figure 1.6). Another problem is that although the efficacy of cover crops to reduce soil erosion is understood in research circles, farmers are not using the techniques that academic articles recommend. There seems to be a communication barrier between researchers and farmers which is detrimental for agricultural sustainability and soil quality.

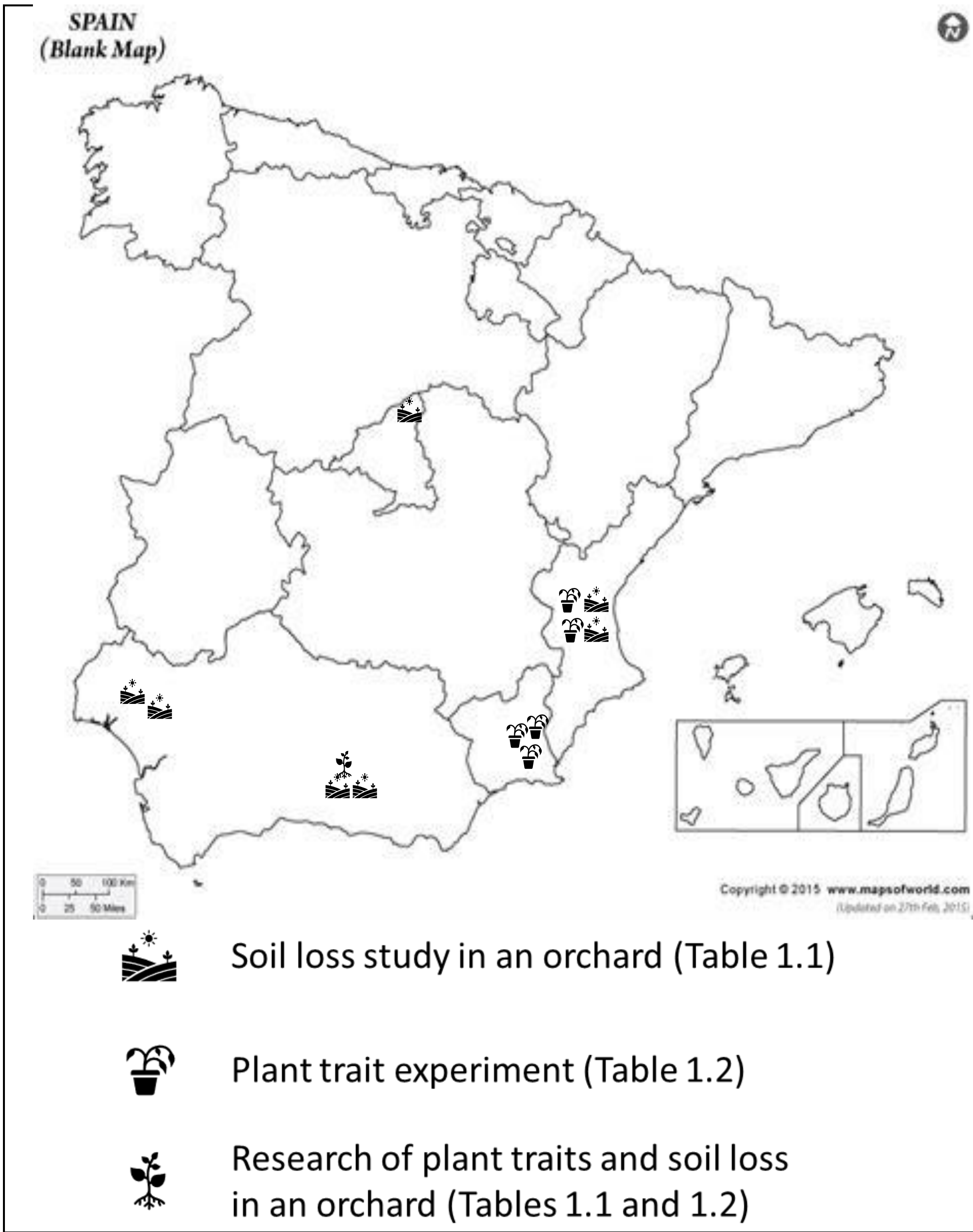


Figure 1.6: locations of the studies reported in Tables 1.1 and 1.2.

Figure 1.4 (repeated below) demonstrates the relationship between olive and orange trees and cover crops, in addition to the key erosion reducing traits for cover crops. These factors are not well understood, the knowledge gaps are highlighted in Table 1.3.

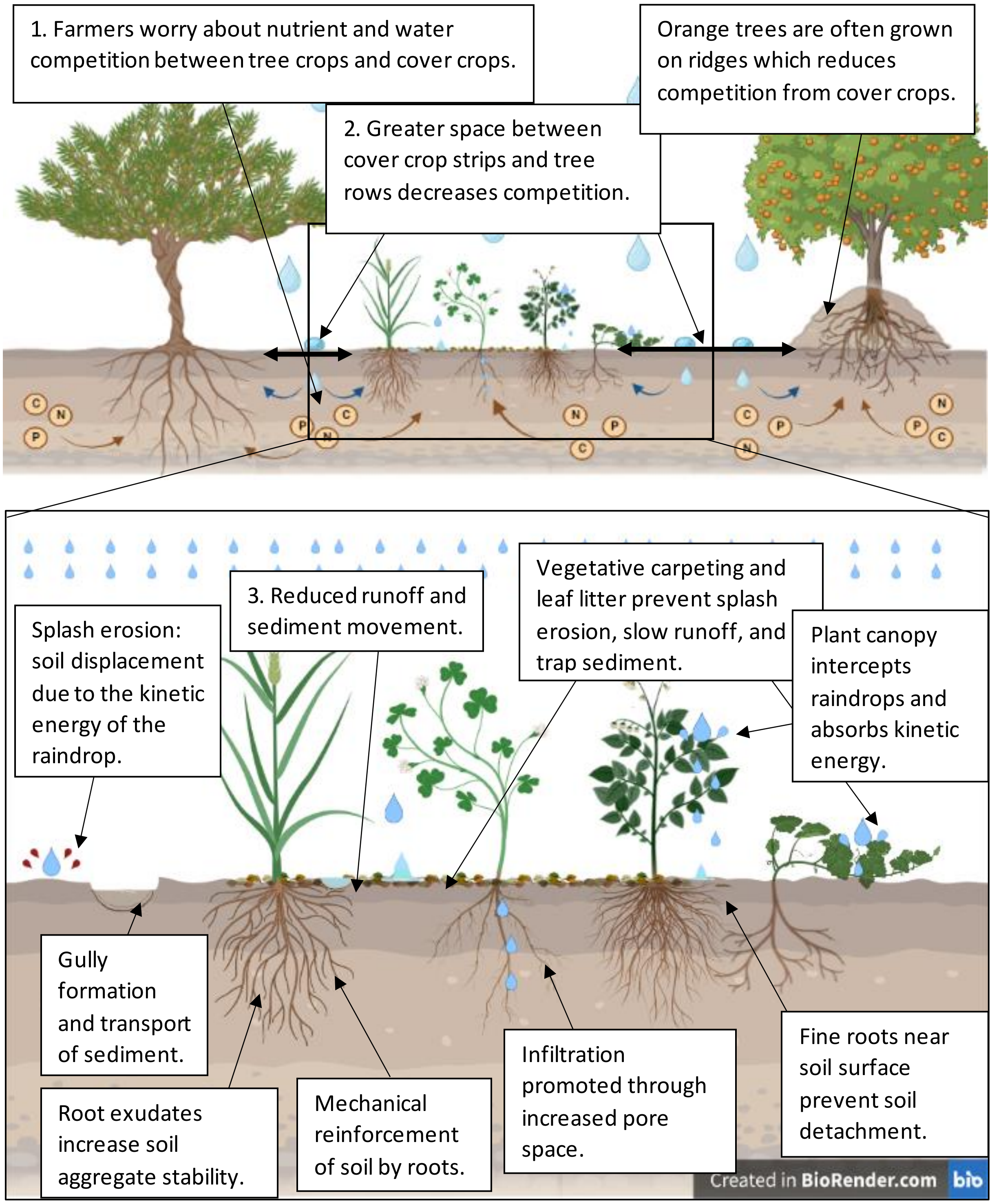


Figure 1.4: An annotated diagram of the impacts of cover crops on tree crops, and above and below ground plant traits on soil erosion and runoff.

Table 1.3: Key knowledge gaps in the area of plant traits and erosion control in Mediterranean orchards.

	Annotation from Figure 1.4	Knowledge gap associated with this factor.
1	Farmers worry about nutrient and water competition between tree crops and cover crops.	Fast growing, annual species have been increasingly used as cover crops in orchards to reduce water competition during the summer. However, the erosion reducing plant traits of these species are under-studied (Figure 1.6). Farmers are not kept informed of all the cover crop research that is carried out, and are slow to take up techniques which are shown to be beneficial.
2	Greater space between cover crop strips and tree rows decreases competition.	There is conflicting evidence about whether cover crops do compete with tree crops. It is not known whether cover crops can increase water and nutrient availability to tree crops. This could happen through reduced evaporation compared to bare soil, promotion of infiltration and increase of C and N in the soil due to plant matter.
3	Reduced runoff and sediment movement.	The efficacy of certain traits to reduce splash erosion is not fully understood. Furthermore, the plant traits of species which are suitable for seasonal use in Mediterranean orchards have not been examined.

1.8 Thesis overview

1.8.1 Aims and objectives

This project was carried out in partnership with Primafruit, a fruit supplier to UK supermarkets including Waitrose. They have many citrus suppliers in Spain who are dealing with soil erosion, so this research was conducted with a view to being applied in the field by these farmers. The objective of this research was to investigate the plant functional traits of fast growing annual species and expand the existing knowledge on the effectiveness of these species to control erosion and their suitability for use in tree crop alleys. The aims of this project are outlined in Table 1.3.

Table 1.4 Research questions for this thesis	
1	Which commonly used seasonal cover crops have beneficial plant traits to prevent soil erosion?
2	Do some of the cover crop species deplete soil nutrients more than others? Are some species more vulnerable to competition from weeds?
3	Which traits are associated with reduced soil loss and runoff?
4	How do farmers deal with soil erosion and is there a communication barrier between farmers and researchers in Spain?

1.7.2 Thesis structure

Following the literature review (Chapter 1), the first data chapter (Chapter 2), detailed an in depth investigation into the above and below ground traits of ten species of plants native to Spain. These species grow as spontaneous vegetation and have been used as cover crops but the traits are not understood (Question 1, Table 1.3). Additionally, evapotranspiration and infiltration were examined due to the water scarcity of the south of Spain. All of the plants were fast growing, easily accessible to farmers, and had no reported assessment of their traits.

Building on Chapter 2, Chapter 3 focused on Aim 2 (Table 1.3) and used the four species with the best plant traits to prevent soil erosion (based on analysis in Chapter 2) in the field, in monocultures and various mixes. Initially this chapter was due to include an assessment of the amount of soil lost from simulated runoff from each treatment. However, due to COVID-19 this could not happen. Nevertheless, soil and plant samples were collected and analysed to determine the impact of the species on soil nutrients and the competition the planted species faced with spontaneous species.

Chapter 4, the third data chapter, used three of the most effective species from Chapter 2 for a mesocosm study to record soil loss under simulated rainfall in response to research question 3 (Table 1.3). Monoculture and a mix were used, and after the rainfall simulation and collection of soil loss, the plants were harvested for above and below ground trait analysis.

Finally, Chapter 5 is the final data chapter. Having established that vegetation cover is effective at preventing soil erosion, and that both above and below ground traits are important factors in achieving this, per Aim 4 (Table 1.3) I wanted to investigate why there had been a low uptake of cover crops by tree farmers in Spain. An online questionaire and in-person interviews were used to study this.

2. Plant trait analysis to determine species beneficial for use as soil erosion cover crops in Spanish orchards

2.1 Introduction

Globally soil is undergoing degradation due to contamination, desertification (23% of all drylands are subject to degradation (Zika and Erb, 2009)), salination and erosion (between 0.2 to 1.5 mm y^{-1}) (FAO, 2019; FAO and ITPS, 2015). Erosion is primarily driven by water and wind (de Graaff et al., 2010), although anthropogenic activities such as agriculture increase the risk of erosion due to land use change and changes to soil physical, chemical and biological indicators of soil health (Sastre et al., 2020). The sparse vegetation, steep slopes, rainfall patterns and anthropogenic activities in the Mediterranean make the soil vulnerable to water erosion (García-Ruiz, 2010; IPCC, 2014). In 2016, severe water erosion (greater than 10 t ha^{-1} yr^{-1}) occurred in 5.31% of the European Union (EU) land area, including 24.93% of Italy, 18.99% of Slovenia, 15.50% of Austria and 9.02% of Spain (EUROSTAT, 2021). This erosion causes rills and gullies to form (Poesen et al., 2003) and reduces soil depth which depletes soil water storage, an important source of water for Mediterranean vegetation (Gómez et al., 2014). Water erosion frequently occurs in vineyards, olive, almond and citrus orchards which are an important part of the Mediterranean economy (Lopez-Vicente and Alvarez, 2018). Soil erosion in Mediterranean farms is controlled through the use of terraces, tillage and cover crops (Zuazo et al., 2009). Tillage is frequently used in hillside orchards to control erosion as it can increase soil roughness which enhances both surface depression storage as well as increasing infiltration by creating macropores and decreasing water erosion (Poesen et al., 2003). However, while contour tillage is more beneficial than conventional tillage (Stevens et al., 2009), the breaking up of soil aggregates and bare soil increases vulnerability to water erosion (Pacheco et al., 2018). Many farmers also use tillage to remove spontaneous vegetation growing between the crop tree rows due to concerns over competition for water and cultural perceptions of cleanliness (Keesstra et al., 2016). However, since the 1990s herbicides have been a preferred means of controlling spontaneous vegetation growth (Vanwalleghem et al., 2011).

While many studies have been conducted into the effectiveness of cover crops to reduce erosion from Mediterranean orchards (Francia Martínez et al., 2006; Gómez et al., 2009a; Keesstra et al., 2016; Raya et al., 2006), these have not been taken up by farmers as a regular practice (Sastre et al., 2017). Acknowledging farmers concerns over water competition in the summer, Gómez et al. (2018) used fast growing annual plants as cover crops. These provided protection from heavy winter rains but could be removed in the summer by the farmers preferred method of either herbicide or tillage. Plant functional traits, such as the fast establishment used by Gómez et al. (2018), can be used to identify plants that prevent splash erosion, trap sediment, and decrease runoff formation which are important features of erosion controlling cover crops (Gyssels and Poesen, 2003; Ruiz-Colmenero et al., 2011; Zuazo and Pleguezuelo, 2008a). Plant functional traits have been researched for their impact on hydraulic roughness (e.g. Burylo et al., 2012), ecosystem functioning (e.g. Lavorel and Garnier, 2002) and plant soil feedbacks (e.g. Baxendale et al., 2014).

Few studies have focussed on plant traits in the context of soil erosion: de Baets et al. (2009), who identified species for rill and gully control in a range of land uses in south-eastern Spain, and Repullo-Ruibérriz do Torres et al. (2018) are among the few. There are many plant traits which are well known to protect soil from erosion. For instance: canopy cover, including above ground biomass and specific leaf area (Bochet et al., 2006; Baxendale et al., 2014); vegetative carpeting, including grass tillers (Xiao et al., 2010), plant height (Raya et al., 2006) and stem elasticity (Dabney et al., 2006); and roots, both diameter (De Baets et al., 2008) and length (Morgan, 2005). However, it is rare that previous experiments have chosen plants specifically because of these traits. Often, if traits are considered or measured, only a small number are thought through for example: evapotranspiration was measured to indicate water use and suitability of the species as an intercrop cover crop in a semi-arid environment (Zuazo and Pleguezuelo, 2008a). But above and below ground traits important for erosion control were not studied. While many traits were examined by de Baets et al. (2009) and Quinton (1997) both papers used some slow growing, perennial plants, such as *Artemisia herba-alba*, *Anthyllis cytisoides* and *Rosmarinus* *officinallis* which would not be suitable for use in orchards with annual vegetation removal (Gómez et al., 2018). The research aim addressed in this chapter was: which commonly used seasonal cover crops or common spontaneous vegetation have beneficial plant traits to prevent soil erosion? This chapter will investigate 11 plant traits of 10 species native to Spain with the aim of selecting species to be used in later field and run off experiments. Above ground (specific leaf area, plant height, tillers, total biomass and stem elasticity) and below ground (below ground biomass, specific and actual root length, and average root diameter) traits will be examined, in addition to infiltration rate and evapotranspiration. The objective of this research was to identify which plant species had the most promising above and below ground traits for controlling erosion. This was assessed by comparing the traits of the respective species and identifying which species had the highest number of erosion controlling traits. As the aim of the chapter was to determine the traits of common species found in Spanish orchards there was no need for control or bare plots. It is hypothesised that some species will exhibit more traits beneficial for controlling soil erosion, however, it is expected that all of the species will have at least one beneficial trait.

2.2 Methods

Laboratory trials were conducted in three stages to assess above ground, below ground and erosion-associated plant traits. The species used are listed in Table 2.1. These species were chosen because they have been previously used in cover crop experiments, in addition to being native to the south of Spain and easily available for farmers to access (Gómez et al., 2018). The seeds were purchased from Semillas Cantueso (Córdoba, Spain).

Table: 2.1 The species used in this chapter, and where the species have previously used.

Species	Studies in which the species have been used
False broom *(Brachypodium distachyon)*	Sastre et al. (2020), García-Díaz et al. (2017), Repullo-Ruibérriz de Torres et al. (2018), Zuazo et al. (2009)
Borage *(Borago officinalis)*	Gómez et al. (2018)
Red broom *(Bromus reubens)*	Repullo-Ruibérriz de Torres et al. (2018), De Baets et al. (2007a)

Field marigold *(Calendula arvensis)*	Gómez et al. (2018), Repullo-Ruibérriz de Torres et al. (2018), Zuazo et al. (2009)
White rocket *(Diplotaxis erucoides)*	Cerdà et al. (2018)
Annual ryegrass *(Lolium rigidum)*	Rodrigues et al. (2015), Gómez et al. (2009a)
Burr medic *(Medicago polymorpha)*	Ovalle et al. (2006) and (2010)
Alfalfa *(Medicago sativa)*	Raese et al. (2007), Cerdà et al. (2021), Li and Pan (2018).
Barrel medic *(Medicago truncatula)*	Soriano et al. (2016)
Bladder campion *(Silene vulgaris)*	Gómez et al. (2018)

Three sets of plants were grown: two in 4 litre pots and the third in infiltration cylinders (Table 2.2). Five replicates were used for each species at each stage of analysis. To ensure uniform bulk density 4kg of soil was weighed into the 4 litre pots. The soil was sieved to 2mm for the second stage of pot trials to make root washing easier. The infiltration cylinders were also filled uniformly. The plants were watered (to 5mm of water on the soil surface) most days, they never went more than two days without being watered. On hot days the plants were watered twice. The ambient temperature in the glasshouse was 22^{o}C.

Table 2.2: Details of the three stages of analysis for Chapter 2.

Analysis	Mesocosm	Analysis conducted
Stage 1: above ground plant traits	4 litre pot, one plant was grown in each pot. There were five replicates for each species.	Specific leaf area, leaf dry matter, plant height, tillers
Stage 2: Primarily below ground plant traits.	4 litre pot, one plant was grown in each pot. There were five replicated for each species.	Stem rigidity and elasticity, biomass weight, actual root length, average root diameter, root volume, root dry matter, specific root length.

Stage 3: Infiltration and evapotranspiration	Infiltration cylinder: PVC pipe with a 100 mm internal diameter, 500 mm height (4, 000, 000 m^{3-} volume), with one end sealed with 2 mm mesh. Three plants of the same species were grown in each cylinder.	Infiltration and evapotranspiration

The plants were grown in glasshouse conditions in Lancaster University. The predominant growth medium was a loamy sand Norfolk topsoil (sand 87%, silt 9% and clay 3%), with mean pH of 7.59 and mean ammonium, nitrate and phosphorus concentrations were 0.003 mg kg^{-1}, 0.775 mg kg^{-1}, and 2.628 mg kg^{-1}, respectively. These parameters were analysed on a SEAL AA3 auto analyser. The seeds grown in pots were first germinated in plug trays with John Innes No. 4 compost. the plants were transferred to pots and cylinders within a week of germination. Approximately 10 seeds were planted directly into the infiltration cylinders, once these were established (within two weeks), the germinating plants were thinned out and the three healthiest were left.

Although the environment was replicated as accurately for the three stages, this experiment took place over several months and the plants were affected by seasonal changes. The glasshouse regulated heat and light but as it was not a controlled environment room there were inconsistencies. There was no need for bare pots for the first two stages of this experiment, but it would have been interesting to have controls for the infiltration and evapotranspiration stage. However, as the aim of the chapter was to assess the traits present in different species, a comparison between the species was all that was required for the third stage.

2.2.1 Leaf analysis

The first part of the trials was focused on the above ground plant traits: specific leaf area, leaf dry matter content, leaf shape, plant height and the number of tillers for grasses. Analysis was conducted 7 weeks after germinating seeds were transferred to pots, when two species (*D. eruoides* and *B. officinalis*) were flowering.

2.2.1.1 Above ground traits

Plants were watered 2 hours before any biomass removal, this only took place 4 hours after sunrise and 4 hours before sunset, to ensure that the leaves were fully extended. Ten fully extended leaves were taken from each plant and photographed on a white background next to a ruler. The leaves were dried at 70 ^{o}C for 72 hours and weighed. ImageJ software (Schneider et al., 2012) was used to determine the leaf area. Mean leaf area for the ten leaves was divided by one tenth of the bulked oven dry mass of the leaves to determine the specific leaf area (cm^2 g^{-1}).

The oven dry mass of the leaves was divided by the fresh mass to determine the leaf dry matter content (mg g^{-1})**.** Plant height (mm) was measured from the soil to the highest point of the canopy, for the bushier plants, such as *B. officinalis*. For the grasses and other less rigid plants, such as *L. rigidum,* the stretched length of the longest part of the plant was measured. The number of tillers for each plant were counted by separating out each shot.

2.2.2 Root analysis and stem elasticity

This part of the laboratory trials focused on both above and below ground plant traits: stem elasticity, biomass weight, specific root length, actual root length and root dry matter content.

2.2.2.1 Stem rigidity and elasticity

Stem rigidity and elasticity was assessed using the modulus of elasticity (GPa). This was measured using the protocol designed by Dabney et al. (1996). A stem was removed at its base and secured horizontally with a clamp. A paper basket was placed at either 150 mm or 50 mm along the stem (*b*), depending on stem length. Fishing weights were added to the basket in 2 g increments, the bending of the stem was recorded in relation to a protractor fixed behind the stem. When the stem no longer returned to its starting position, the angle of bending with no weights attached (*V*) and the mass of the fishing weights in the basket were recorded. The stem was cut at the point where the weights had been added, the internal (D_a) and external (d_1) diameter of the stem were recorded. Where the stem was not circular these diameters were recorded for both the major (d_a and d_1) and minor (d_b and d_2) axes. The moment of inertia (I) was calculated using equation 1 for circular stems and equations 2 and 3 for oval stems that bent on the minor and major axis respectively.

(1) $I = \frac{\pi}{64}(d_i^4 - d_a^4)$

(2) $I_{min} = \frac{\pi}{64}(d_2^3 d_1 - d_b^3 d_a)$

(3) $I_{maj} = \frac{\pi}{64}(d_1^3 d_2 - d_a^3 d_b)$

The angle of deflection (Δ) was calculated using the angle of bending (V) and the length along the stem (b) in equation 4.

(4) $\Delta = tan(\frac{V\pi}{180})b$

The moment of inertia (I) and the angle of deflection (Δ) were used in equation 5 to find the modulus of elasticity (E). The mass of the basket and the fishing weights that exceeded the elasticity of the stem was converted into Newtons (P).

(5) $E = \frac{Pb^3}{3I\,\Delta}$

2.2.2.2 Below ground analysis

For biomass weight, all the plant material was dried at 70 ^{o}C for 72 hours then weighed to determine the oven dry weight.

The whole of the plant root was analysed. While every effort was made to collect and wash all the roots, a time limit of 2 hours of root washing per plant was established. The washed roots were stored at 5^{o}C in air-tight containers in ethanol and milliQ water.

The roots were scanned using an Epson Expression 11000 XL scanner. Due to the size of the root mass several scans were required for each plant. The scanned images were analysed using winRHIZO Pro 2013e 32-Bit software. This software calculated the actual root length (m), average root diameter (mm) and root volume (cm^2). After scanning the roots were dried at 70^{o}C for 72 hours and weighed to find the below ground dry weight (DW) biomass (g). The actual root length was divided by the below ground DW biomass to determine the specific root length (m g^{-1}).

2.2.3 Infiltration and evapotranspiration analysis

Infiltration cylinders (100 mm internal diameter, 500 mm height with one end sealed with 2 mm mesh) were filled with Norfolk topsoil and seeded; three plants were grown in each cylinder.

The water balance method was used to assess the evapotranspiration rate (g cm^{-2} day^{-1}): the plants were well watered (to 5mm water on the surface of each cylinder) and weighed (W_0), the weight of the cylinders was recorded after 24 hours (W_1) and the plants watered (±1 g of W_0). This was repeated for five days. The water use per day was determined by $W_0 – W_1$. The mean water use was divided by the leaf area of the plant to calculate the evapotranspiration rate (g cm^{-2} day^{-1}).

To measure infiltration (cm s^{-1}), the plants were well watered and left for 24 hours before the above ground biomass was removed to soil level. A 5 cm diameter infiltration ring was driven 0.5 cm into the soil and filled with 150 cm^3 of water, the time taken for all the water to infiltrate into the soil was recorded. The maximum amount of time allowed for infiltration was 30 minutes.

2.2.4 Statistics

ANOVA, Tukey post-hoc and Levene tests were carried out on the data. The significance threshold was $p < 0.05$. Statistical analysis and graph production was carried out using RStudio Version 1.3.1056.

2.3 Results

2.3.1 Above ground traits

There was no significant difference between any of the species for specific leaf area (SLA), however there was a large range: false broom (*B. distachyon)* at 369 cm^2 g^{-1} SLA, while white rocket (*D. erucoides)* had 179 cm^2 g^{-1} (Figure 2.1a). There was no significant difference in the variations of the species.

Annual ryegrass (L. rigidum) (635.6 mm) and bladder campion (*S. vulgaris)* (580.2 mm) were the tallest species, the shortest species was field marigold (*C. arvensis)* (209.4 mm) (Figure 2.1b). There was a significant difference in the variation of the height of the species. White rocket (*D. erucoides)* had the largest mean modulus of elasticity (MoE) at 4.826 GPa and borage (*B. officinalis)* had the smallest mean MoE at 0.205 GPa (Figure 2.1c). The Levene test revealed a significant difference in the variation of the MoE of the species. The above ground dry biomass (AGB) was greatest for borage (*B. officinalis)* and white rocket (*D. erucoides)* at 5.55 g and 5.51 g, respectively (Figure 2.1d). Alfalfa (*M. sativa)* had the smallest biomass at 1.79 g (Figure 2.1d). There was a significant difference in the variances of biomass of the species. The mean tillers for false broom (*B. dista)* and red broom (*B. rubens)* were similar with 33.6 and 32.4 mean tillers per plant, respectively. Annual ryegrass (*L. rigidum)* had the lowest mean number of tillers at 12.8 per plant. The variation in the tillers for each species was significantly different.

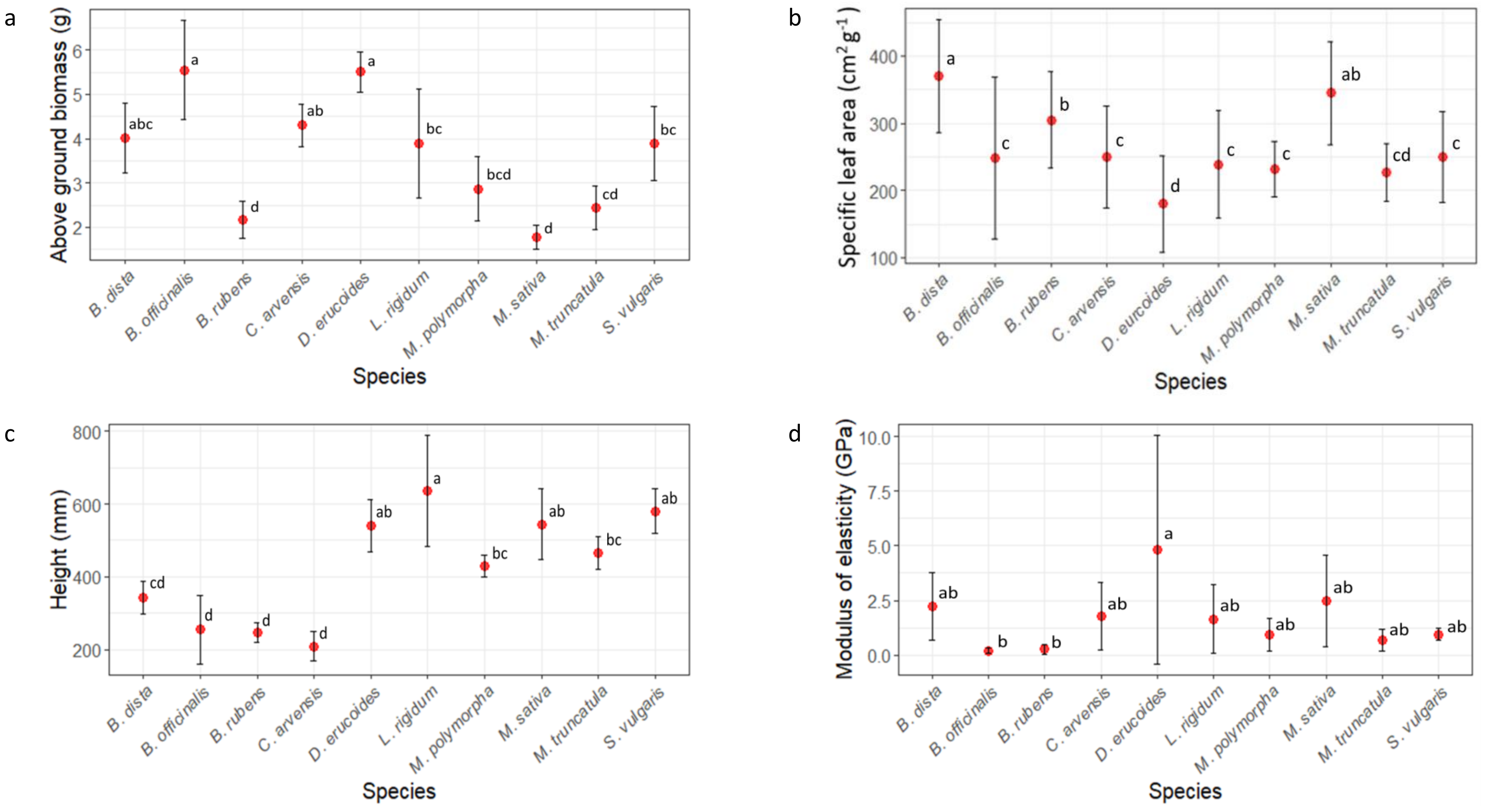


Figure 2.1: Above ground traits: (a) specific leaf area (cm2 g-1), (b) height (mm), (c) biomass (g), and (d) modulus of elasticity (GPa). The larger red points in each figure represent the mean for each species, with error bars showing the standard deviation.

2.3.2 Below ground traits

False broom *(B. dista)* and annual ryegrass (*L. rigidum)* had the largest mean actual root length (ARL) at 234.2 m and 255.5 m, respectively (Figure 2.2a). Alfalfa (*M. sativa)* had the lowest mean ARL, 32.7 m (Figure 2.2a). There was no significant difference in the variations of the species for ARL or specific root length (SRL). The mean SRL was highest for red broom (*B. rubens)* at 694.25 m g^{-1}, alfalfa (*M. sativa)* had the lowest mean SRL, 96.73 m g^{-1} (Figure 2.2b). Annual ryegrass (*L. rigidum)* and borage (*B. officinalis)* had the largest mean below ground biomass (BGB) with 0.636 g and 0.587 g, respectively (Figure 2.2c). Barrel medic (*M. truncatula)* had the smallest mean root dry matter at 0.14 g (Figure 2.2c). There was no significant difference in the variance of the BGB recorded for the species. However, there was a significant difference in the standard deviation noted for the average root diameter (ARD). The species with tap roots had the highest ARD: barrel medic (*M. truncatula)* had the largest mean ARD at 0.312 mm; followed by burr medic (*M. polymorpha)* (0.29 mm), field marigold (*C. arvensis)* (0.27 mm) and white rocket (*D. erucoides)* (0.27 mm) (Figure 2.2d). False broom (*B. distachyon)* and annual ryegrass (*L. rigidum)* had the smallest average root diameter at 0.16 mm (Figure 2.2d). The largest mean root volume (RV) was found in annual ryegrass (*L. rigidum)* at 6.01 cm^{-2} (Figure 2.2e), this was not significantly different from any other species. Alfalfa (*M. sativa)* had the smallest mean RV at 1.41 cm^{-2}. There was also a significant difference in the variation of RV of the replicates of the species studied.

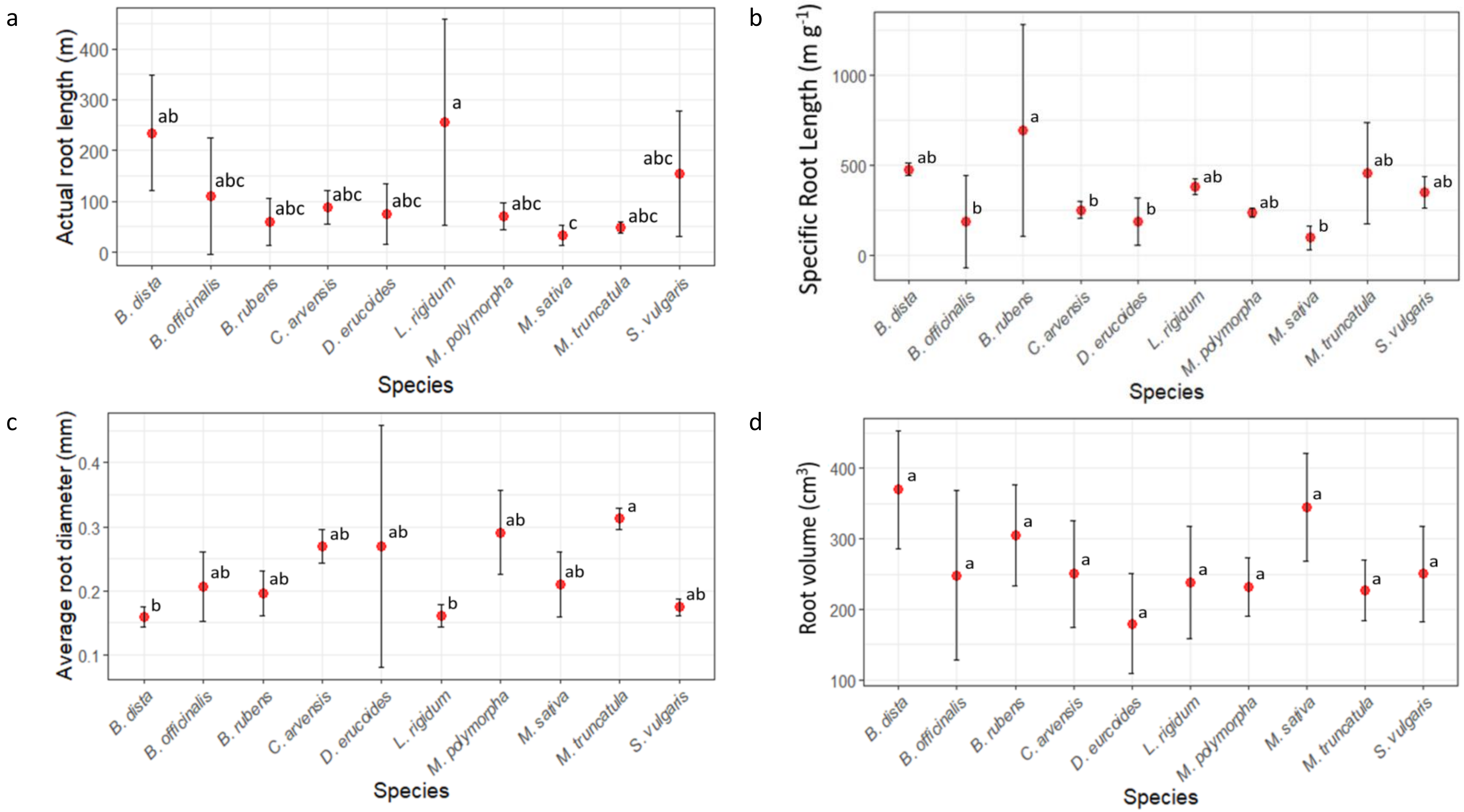


Figure 2.2: Below ground traits,(a) actual root length (m), (b) specific root length (m g^{-1}), (c) average root diameter (mm), (d) root volume (cm^3). The larger red points in each figure represent the mean for each species, with error bars showing the standard deviation.

2.3.3 Evapotranspiration and infiltration

The species with the largest evapotranspiration was white rocket (*D. erucoides)* with a mean of 1.69 g cm^{-2} day^{-1}..The lowest mean evapotranspiration rate was for burr medic (*M. polymorpha)* (0.17 g cm^{-2} day^{-1}). See Figure 2.3a for significant differences. The degree of variation of evapotranspiration within each species was significantly different.

a

b

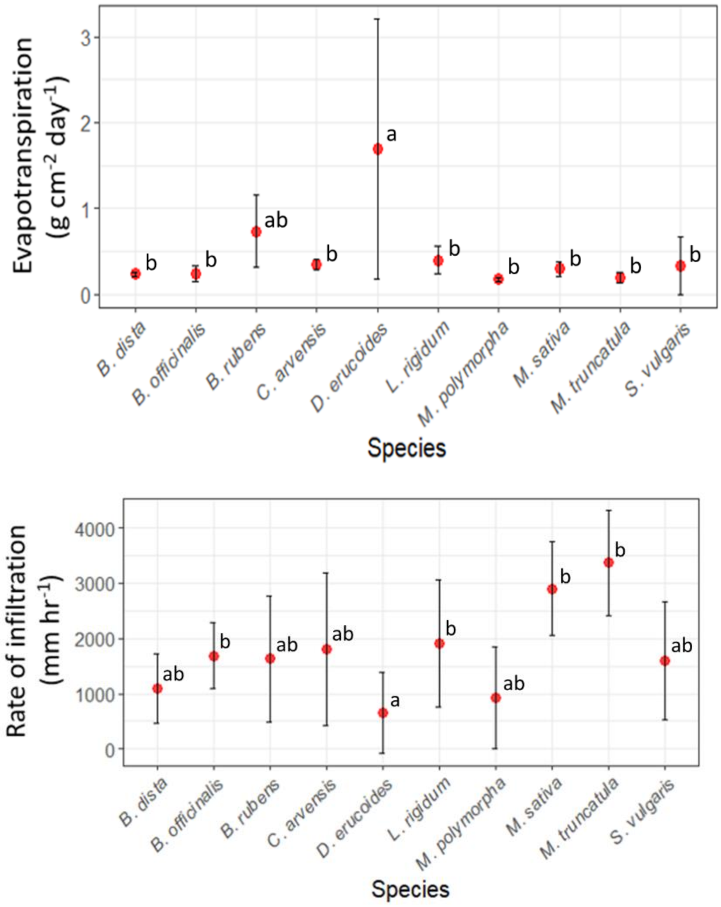


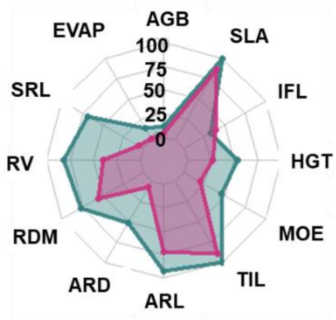
Figure 2.3: (a) Evapotranspiration (g cm^{-2} day^{-1}) and (b) infiltration (mm hr^{-1}). The larger red points in each figure represent the mean for each species, with error bars showing the standard deviation.

White rocket *(D. erucoides)* had the slowest mean infiltration at a rate of 660 mm hr^{-1} (Figure 2.3b). This species was significantly slower than alfalfa (*M. sativa)* and barrel medic (*M. truncatula)* ($p < 0.05$). The fastest mean infiltration rate was observed for barrel medic (*M. truncatula)* (3370 mm hr^{-1}) (Figure 2.3b). Barrel medic (*M. truncatula)* was significantly faster than false broom (*B. distachyon)* and borage (*B. officinalis)* ($p < 0.05$). There was no significant difference in the amount of variation within the species.

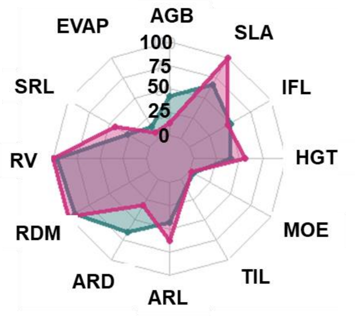
2.3.4 Radar graphs

The radar graphs (Figure 2.4) indicate proportionally how the species performed for each parameter. The mean for each parameter is shown as a percentage of the highest mean, with 100% on the outside of the graph. For example, false broom (*B. distachyon)* had the highest mean specific leaf area (SLA) at 369 cm^2 g^{-1}, therefore SLA is plotted at 100% on the false broom (*B. distachyon)* radar graph. The second highest mean SLA was alfalfa (*M. sativa)* at 345 cm^2 g^{-1}, so SLA is plotted at 93% on the alfalfa (*M. sativa)* radar graph. The radar graphs illustrate the relative outcome of species compared to the other species examined in this chapter, there was no weighting applied. The outside of the radar plots indicate the highest mean value for each parameter. Depending on the parameter, this may or may not indicate a greater potential to reduce erosion.

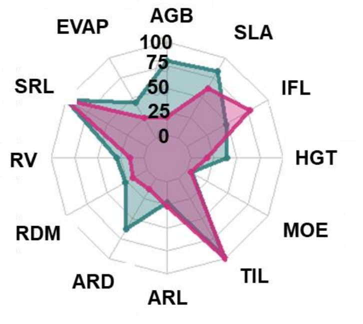
Figure 2.4: Radar graphs representing each species' erosion reducing potential based on each parameter measured. The blue section shows how the mean of the data for each species compared to the mean of the other species for that parameter. The pink part indicates the relative range.



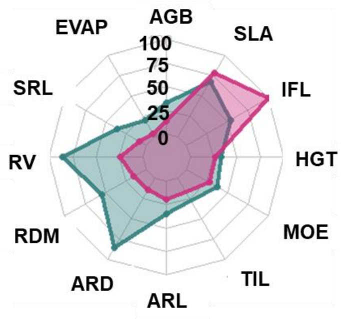
B. dista



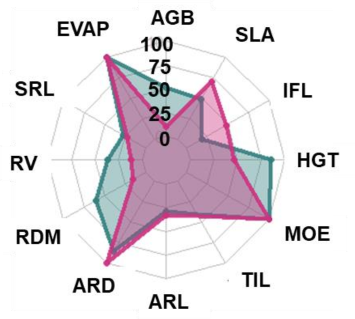
B. officinalis



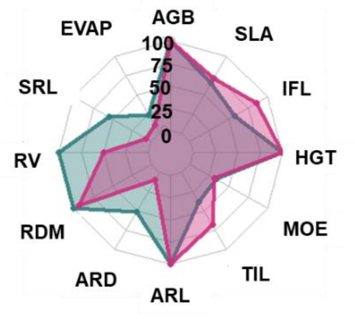
B. rubens



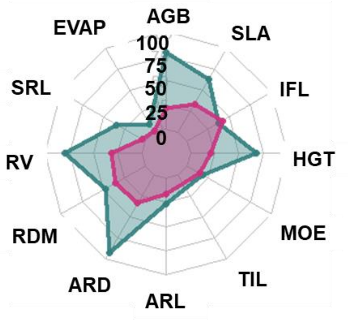
C. arvensis



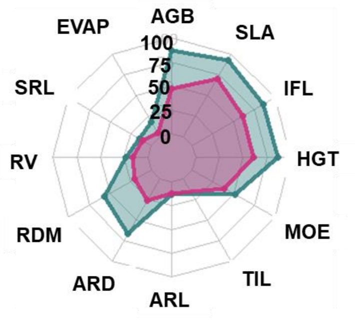
D. erucoides



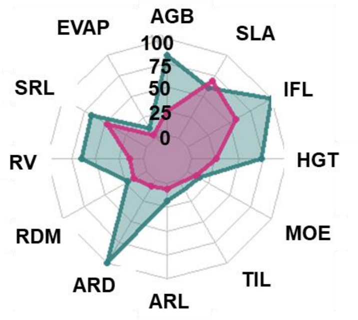
L. rigidum



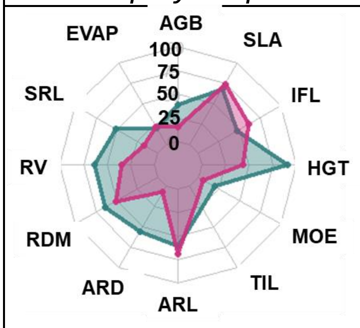
M. polymorpha



M. sativa



M. truncatula



S. vulgaris

Key

Splash erosion traits: biomass (AGB) and specific leaf area (SLA)

Runoff interception: infiltration (IFL), height (HGT), modulus of elasticity (MOE)

Soil reinforcement: actual root length (ARL), average root diameter (ARD), root dry matter (RDM), root volume (RV), specific root length (SRL)

	Environmental suitability: evapotranspiration (ET)

2.4 Discussion

Splash erosion is caused when a raindrop hits bare soil, however covering the soil with plant residue or living plant cover protects the soil (Gyssels et al., 2005; Palese et al., 2014). The amount of protection provided by different species can be considered by comparing the specific leaf area (greatest for false broom (*B. distachyon)*, 369 cm^2 g^{-1}, and alfalfa (*M. sativa),* 345 cm^2 g^{-1}, Figures 1a and 4), which is a measure of canopy cover (Burylo et al., 2012). Additionally, plants with large above ground biomass, such as borage (*B. officinalis)*, 5.55 g, and white rocket (*D. erucoides),* 5.51 g (Figures 1c and 4), offer more protection from splash erosion (Morgan, 2005; Bochet et al., 2006).

Another form of water erosion, which is a major issue in Spain, is runoff erosion resulting in rills and gullies. A survey by Borrelli et al. (2021) recorded 211 sites of gulley erosion in the EU and UK, of which 61% were identified in Spain. This is particularly problematic in hillside orchards due to the slope and the practice of removing weeds (Moore et al., 2008; Keesstra et al., 2016). Increasing the infiltration rate of the surface water reduces runoff formation and replenishes groundwater supplies (Poesen et al., 2003; Zuazo and Pleguezuelo, 2008a). Figure 3b indicates that barrel campion *(M. truncatula)* and alfalfa (*M. sativa)* both had high infiltration rates of 3370 mm hr^{-1} and 2900 mm hr^{-1}, respectively. Barrel campion (*M. truncatula)* also had the largest mean root diameter (0.312 mm) (Figure 2.2d) which is unsurprising as plant roots increase the pore space and pore space connectivity in the soil, and are an important influence on infiltration (Ruiz-Colmenero et al., 2013; Keller et al., 2018). However, the die back of the roots is a key factor in their influence on pore space, and as infiltration was carried out on flowering plants the full potential impact of the roots on infiltration would not have been observed (Keller et al., 2018). Slowing down and allowing the runoff to pool facilitates infiltration and sediment deposition (Xiao et al., 2010; Raya et al., 2006), this is enabled by high stem count, vegetative carpeting and trapped litter (Raya et al., 2006; Zuazo et al., 2009). Ground hugging plants, such as field marigold (*C. arvensis),* the shortest plant at 209 mm (Figure 1b), and grasses with a higher number of tillers, such as false broom (*B. distachyon)* (mean tiller count 33.6) (Figure 4), not only slow down overland flow but also trap sediment (Xiao et al., 2010). Occasionally plants may be bent under the intensity of the rainfall, or due to overland flow. In these instances plants that have a high modulus of elasticity, such as white rocket (*D. erucoides)* (4.826 GPa) (Figure 2.1d), are beneficial as they are more resilient (Dabney et al., 1996; Burylo et al., 2012).

In addition to influencing infiltration, below ground traits also indicate the effect of plants on sediment trapping and soil reinforcement (Morgan, 2005; De Baets et al., 2008). Roots with small diameters, such as those of false broom (*B distachyon)* and annual ryegrass (*L. rigidum)* (both 0.16 mm) (Figure 2.2d), can form a root mat close to the surface of the soil which, during overland flow events, prevents soil detachment (Gyssels and Poesen, 2003; De Baets et al., 2006). Furthermore, fibrous roots indicated by high specific root length, for instance red broom (*B. rubens) (694 m* g^{-1}*)* (Figure 2.2b), provide reinforcement to the soil by increasing the tensile strength of the soil matrix and, at the surface, can prevent the detachment of soil (Morgan, 2005; De Baets et al., 2006). The specific root length noted were lower than observed by Baxendale et al. (2014) for monocultures but higher than the results for a mixture. The difference could be due to the larger mesocosms used by Baxendale et al. (2014) as the growth period between the experiments was only one week different. Annual ryegrass (*L. rigidum)* and false broom (*B. distachyon)* (Figure 2.2a) had the largest actual root length (256 m and 234 m, respectively), so would be able to provide reinforcement deeper in the soil profile and to a wider area of soil (Morgan, 2005). Both root volume and root dry matter of annual ryegrass (*L. rigidum)* and borage (*B. officinalis)* have large standard deviations (Figure 2.2c and 2.2e). However, the large means for both of these parameters indicate that a large area of soil is reinforced (Figure 2.4) which would make them still acceptable for use as cover crops (Gyssels et al., 2005).

Cover crops are used to control erosion in many regions, this plant trait analysis was to gain insight into cover crop suitable for use in semi-arid Spain. Therefore, the water use efficiency and potential competition for water between cover crops and tree crops was an important consideration (Gómez et al., 2018). While all of the species analysed are native to southern Spain and can withstand dry periods, burr medic (*M. polymorpha)* and barrel medic (*M.*

truncatula) had the lowest mean evapotranspiration rates showing that they could cope particularly well with low water availability (Figures 2.3a and 2.4) (Zuazo and Pleguezuelo, 2008a).

Not all of the traits fit neatly into the radar diagrams (Figure 2.4). For example small average root diameter indicates fibrous roots which provide soil reinforcement (Loades et al., 2010). Whereas a large average root diameter suggests tap roots which, after die back, leave large pore spaces and encourage infiltration (Keller et al., 2018). However, the radar graphs (Figure 2.4) demonstrate that no one species performed exceptionally on all traits and neither was this expected; and the graphs signpost the usefulness of plant mixes as cover crops (Ghestem et al., 2014). Plant mixes allow plants with beneficial below ground traits, such as false broom (*B. distachyon)* (Figure 2.2a and d) and *M. sativa* (Figure 2.2d), to be used in the same plots as plants with ideal above ground traits, field marigold (*C. arvensis)* (Figure 2.1b) and bladder campion (*S. vulgaris)* (Figure 2.1d).

The variation within the species was also an important factor as this indicated how consistent the development of the plants was (Figure 2.4). This also signposted the reliability of the species if selected for an erosion control cover crop based on their traits. Temperature, light quality and quantity are the primary causes of differences in plants growth (Poorter et al., 2016). However, these were all the same for all the species in the greenhouse. None of the species had the lowest or highest range for all of the parameters (represented by the pink area in the radar graphs, Figure 2.4). The legumes (*M. polymorpha, M. sativa* and *M. tuncatula*) had the smallest pink areas. This indicated there was less variation between the replicates of these species, particularly for below ground parameters. As plant functional type is a major influence on trait variation (Freschet et al., 2017), this is unsurprising. False broom (*B. dista*) and alfalfa (*M. sativa*) were the only species where the relative variation within the replicates was not greater than the relative mean. This is shown by the pink area of the radar graphs not exceeding the blue area (Figure 2.4), which suggests that these species were consistent in their growth. This variation in traits is not unusual, Freschet et al. (2017) identified high root trait variation at local scales.

2.5 Conclusions

Plant traits analysis had useful outputs for comparing species prior to use as erosion control cover crops. White rocket (*D. erucoides)* would not be recommended to control erosion in Spain due to the high evapotranspiration and slow infiltration (Figure 2.3), in addition to small actual root length and root volume (Figure 2.2). False broom (*B. distachyon), red broom (B. rubens), alfalfa (M. sativa)*, and bladder campion (*S. vulgaris)* all had a good combination of ideal above and below ground traits. False broom (*B. distachyon)* had high root volume and specific leaf area, and red broom (*B. rubens)* was low lying with high specific root length. Alfalfa (*M. sativa)* had high specific leaf area, large root volume and was associated with high rate of infiltration, bladder campion (*S. vulgaris)* had large above ground biomass and specific root length (Figures 2.1, 2.2 and 2.3).

Planting mixtures of these species may allow a combination of above and below ground traits from different species to be utilised in one plot. Additionally, plant mixtures have many other benefits, including the nitrogen fixing properties of legumes and biodiversity (Finney et al., 2016). Therefore, false broom (*B. distachyon)*, red broom (*B. rubens)*, alfalfa (*M. sativa)* and bladder campion (*S. vulgaris)* were used in both monocultures and mixes in the field in Chapter 3.

3. Impact of cover crops on soil and plant chemistry in an olive orchard in southern Spain

3.1 Introduction

In the semi-arid environment of southern Spain, water is a key limiting factor for the growth of tree crops such as citrus, stone fruit and olive (Ruiz-Colmenero et al., 2013; Gómez et al., 2018). One of the concerns that farmers have with the use of vegetative cover to control water erosion between tree rows is that it will cause the tree crops to lose yield due to competition for water (Taguas and Gómez, 2015; Raya et al., 2006). However competition for nutrients could also result in yield loss (Gucci et al., 2012). While some studies reveal that the water and nutrient competition concerns are well founded and that cover crops cause a decrease of yield in tree crops (Ruiz-Colmenero et al., 2011; Gómez, 2005; Gucci et al., 2012), other studies find that this is not the case (Keesstra et al., 2016; Ruiz-Colmenero et al., 2013). However, the establishment of the olive trees could also affect the impact of water and nutrient competition on the yield. Older trees (three to four years after planting) are better able to cope with the water usage of permanent vegetative cover than younger trees (Gucci et al., 2012).

It is well recognised that vegetation cover, including cover crops, have an impact on soil chemistry and microbial communities (Fernandez et al., 2016; Cardinali et al., 2014). Many studies indicate that cover crops provide benefits for soil nutrients, as they prevent the leaching of nutrients, such as N, from the bare soil, in addition to retaining nutrients in the soil that would otherwise have been lost due to soil erosion (Sainju et al., 2005; Jang et al., 2021; Lee et al., 2014; Gómez et al., 2009a). Cover crops also provide weed suppression benefits, outcompeting spontaneous species which may have high water use or harbour pests (Chen et al., 2019; Hollander et al., 2007). The subsequent impact of cover crops has been researched with regard to successional cash crops in red pepper (Lee et al., 2014), integrated cropping systems (Jahanzad et al., 2016), corn (Liebman et al., 2018) and cotton (Rochester and Peoples, 2005).

Cover crops have been shown to have a positive effect on tree crops (e.g. Rodrigues et al., 2011). Furthermore, legumes grown as a cover crop were shown to have a positive impact on tree crop yields in olives (Rodrigues et al., 2015), grapevines (Ovalle et al., 2010) and coffee shrubs (Snoeck et al., 2000). Isotope analysis was carried out by Ovalle et al. (2010) and Snoeck et al. (2000) which indicated that the amount of N legumes delivered from cover crops to coffee trees and grapevines, respectively, rival that of N fertiliser. However, Rodrigues et al. (2013) warned that senescence of legumes in the autumn reduced the transfer of N to tree crops due to heavy rainfall in this season which caused leaching and runoff. Nonetheless a cover crop mix with non-legumes is suggested to slow the mineralisation of the legumes for the benefit of the tree crops (Rodrigues et al., 2013).

The aim of this chapter was to identify whether cover crop treatments planted in an olive orchard in Andalucía resulted in any change in soil chemistry. These changes could affect the tree crops, and to identify how the planted species interact with weeds (i.e. spontaneous vegetation). It was hypothesised that where the legume was planted there would be higher soil N. It was also hypothesised that the plots with the greatest cover would result in the greatest change in soil chemistry, and the most effective suppression of harmful spontaneous vegetation.

3.2 Methods

3.2.1 Field set up

Plots were set up in an olive orchard 60 km south of Cordoba, in a silty clay loam (35% clay, 56% silt, 9% sand) soil. A map of Spain with the location of the field site pinned is show in Figure 3.1.

Figure 3.1: Map of Spain with the location of the field site highlighted in red. Source: Google Maps, 2021.

Four species of cover crop seeds were purchased from Semillas Cantueso (Córdoba, Spain), these were planted in mixes and monocultures described in Table 3.1. Two grasses, false broom (*Brachypodium distachyon)* and red broom (*Bromus rubens),* a legume, alfalfa (*Medicago sativa)*, and one forb, bladder campion (*Silene vulgaris)*, were used in both monocultures and mixes. These species were chosen as they had a good mixture of traits and this experiment was designed to further research the traits of these species. A grass was present in all of the mixtures as the two grass species had low water use and a good range of erosion preventing traits (Chapter 2). Seeding rates were based on previous studies using these species, and the outcome of the germination trial in Chapter 2.

Table 3.1: The codes of the treatments used, the species in the treatments and the seeding rate of the treatments.

Grass (G)1	False broom (*Brachypodium distachyon)*	6 g m^{-1}
G2	Red broom (*Bromus rubens)*	6 g m^{-1}
Forb (F)1	Bladder campion (*Silene vulgaris)*	3 g m^{-1}
Legume (L)1	Alfalfa (*Medicago sativa)*	3 g m^{-1}
G1F1	False broom (*B.distachyon)* and bladder campion *(S. vulgaris)*	3 and 1.5 g m^{-1} respectively
G1L1	False broom (*B. distachyon)* and alfalfa *(M. sativa)*	3 and 1.5 g m^{-1} respectively
G1L1F1	False broom (*B. distachyon), alfalfa (M. sativa)* and bladder campion *(S. vulgaris)*	3, 1 and 1 g m^{-1} respectively
G2F1	Red broom *(B. rubens)* and bladder campion *(S. vulgaris)*	3 and 1.5 g m^{-1} respectively
G2L1	Red broom *(B. rubens)* and alfalfa *(M. sativa)*	3 and 1.5 g m^{-1} respectively
G2L1F1	Red broom *(B. rubens),* alfalfa *(M. sativa)* and bladder campion *(S. vulgaris)*	3, 1 and 1 g m^{-1} respectively
G1G2L1F1	False broom *(B. distachyon),* red broom *(B. rubens), alfalfa (M. sativa)* and bladder campion *(S. vulgaris)*	1.5, 1.5, 1 and 1 g m^{-1} respectively

Seeds were planted in October 2019 and the plots were weeded in December 2019 and February 2020 before being harvested in April 2020. Harvesting took place when the plants were flowering. No mineral fertilisers were added to the treatments. The treatments were laid out in a randomised design, with five replicates for each treatment. No control plots were used as the aim of the experiment was to examine the impact of traits on soil loss, so species were required to provide the necessary information. The lack of control plots restricted the experiment to comparison between vegetated plots and it was not possible to identify soil changes caused by the plants. However, this plan was interrupted by COVID-19 as explained in section 3.2.2. A ECRN- 50 low resolution rainfall (specified for measuring irrigation events) gauge and an ECT/RT-1 air temperature sensor were installed, data was collected via a ECH2O Utility logger. Additionally, Delta-T ML3 Theta soil moisture probes were buried in the soil profile at depths of 10 cm, 20 cm, 30 cm, 40 cm and 50 cm. The theta probes were connected to a DL6 Delta Link data logger. Figure 3.2 is a photograph of part of the field site, the treatment plots, row of olive trees and position of the sensors and probes are shown.

Figure 3.2: A view of the field site with the probes and sensors, olive rows and one treatment annotated. A second row of treatment plots is out of shot.

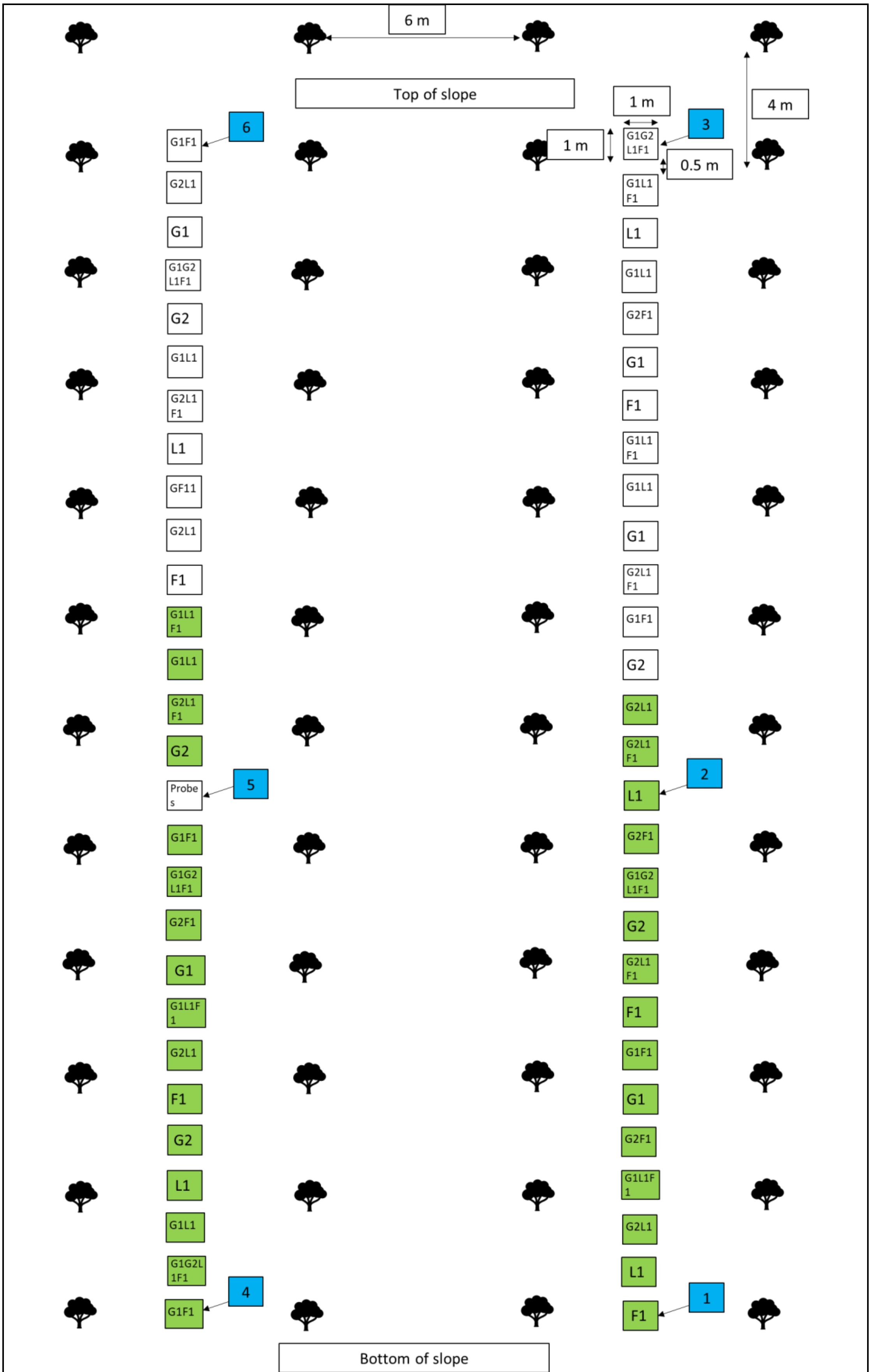


Figure 3.3: Schematic diagram of the field lay out. The green plots were sampled, the blue numbers indicate where samples for starting field parameters (Table 3.2) were taken.

3.2.2 Impact of COVID-19

The original plan for this experiment was to conduct runoff analysis on the plots in April 2020. Soil lost from each plot would have been collected and a simplified version of the plant trait analysis in Chapter 2 carried out. However, at this time COVID-19 hit the UK and boarders were closed so it was not possible to travel to the field site. Collaborators in Spain were able to go to the field site for short periods of time to collect soil and plant samples.

While it was not possible to continue with the planned methodology, enough samples were gathered to be able to compare the development of the planted species in the different treatments. The dried above ground biomass was separated into the different species where possible (in a handful of instances it was not possible to tell the grasses apart). The soil samples were dried and stored until the lab analysis could take place.

3.2.3 Laboratory analysis

Samples were collected from 33 plots, giving three replicates of each of the 11 treatments (Figure 3.3). Above ground biomass was removed and oven dried (60°C until constant weight), one soil sample to 10 cm depth was collected and oven dried (also, 60°C until constant weight) from each plot, additionally soil samples were taken from around each of the soil moisture probes, these were kept cool to prevent moisture loss. The soil from around the soil probes was used to calibrate the theta probes, following the guidelines in the Delta-T (Devices, 2017) ML3 Theta probe hand book.

Olsen P (Olsen et al., 1954) extracts were made by mixing 2 g of soil with 40 ml 0.5M $NaHCO_3$; ammonium and nitrate extracts were taken by mixing 5 g of soil with 100 ml 2M KCl. Both extracts were placed in an orbital shaker for 30 minutes before being allowed to settle. Then the extracts were filtered and stored in the fridge for a week until ready for analysis. The extracts were analysed for P, ammonium and nitrate on a SEAL AA3 auto analyser, alongside blanks which were used to adjust the data for instrument error.

For loss on ignition, the weight of the empty crucibles (W_c) was noted and 10 g of soil was added. The crucibles were put in a 105 °C oven over night and the oven dry weight (W_{dry}) was recorded. The crucibles were then transferred to a

550 ^{o}C furnace for 6 hours, they were left to cool overnight, and the weights were recorded (W_{OML}). The following equation was used to calculate the percentage of organic matter in the samples:

$$OM(\%) = \frac{W_{dry} - W_{OML}}{W_{dry}} \times 100$$

The dried plant biomass from each plot was separated into individual species and weeds. This was weighed and recorded. A small amount of each species was ball milled and 10 mg of each sample was analysed using the Elementar vario EL cube CN analyser to find the plant N and plant C.

Photographs were taken (using digital cameras and phones) of each plot from one meter above the plot, shadows were avoided. These photographs were analysed to identify the percentage of soil cover per plot using soil cover software (the Soil Cover App) designed in a collaborative project of Josephinum Research, Istitut für Kulturtecknik und Bodenwasserhaushalt and BLT Wieselburg Fransisco Josephinum.

3.2.4 Statistical analysis

The data was analysed with a Shapiro Wilkes test to identify normal and non-normal data sets. The normal data was analysed with an ANOVA and the non-normal with a Kruskal-Wallis test. A Tukey post-hoc test was used to identify significant differences between species or treatments. The significance threshold was $p < 0.05$. Statistical analysis and graph production was carried out using RStudio Version 1.3.1056.

3.3 Results

The results indicate that there was no significant difference between the cover crops on soil chemistry (Figure 3.3). Figure 3.4a shows that *M. sativa* contained significantly more plant N than the other species, but the biomass and chemistry of all of the species indicate nutrient rich litter.

Prior to the planting of the treatments, six equally spaced soil samples were taken (Figure 3.3), the parameters measured is shown in Table 3.2. The subsamples of the six soil samples were analysed for Olsen P.

Table 3.2: The chemistry of six soil samples taken from the treatment rows before the treatments were planted.

	pH	Olsen P (mg kg^{-1})		Organic matter (%)	Ammonium (mg kg^{-1})	Nitrate (mg kg^{-1})
Sample		Mean	St dev			
1	8.57	21.73	1.16	7.35	0.151	0.379
2	8.54	11.33	0.87	7.03	0.239	0.325
3	8.18	7.51	0.79	6.25	0.257	0.257
4	8.13	36.34	1.27	8.16	0.361	0.199
5	8.03	11.58	1.04	6.15	0.163	0.67
6	8.07	9.00	0.69	6.39	0.204	0.281

The ammonium and nitrate (mg kg^{-1}) values (Table 3.2) are considerably lower than the treatment samples (Figure 3.3a and b). This may be due to the extracts of the bare soil being kept in a freezer for over a year, due to COVID-19, causing a degradation of the N. Also, ammonium and nitrate in the soil varies with the differences in season and weather conditions a the time of collection. The cover crops could also have had an effect but with so many variables it is impossible to know.

Figure 3.3a shows that ammonium in the soil samples ranged from 44.05 mg kg^{-1} in a G1G2L1F1 plot and 1.17 mg kg^{-1} under a G1L1F1 treatment, there was no significant difference ($p < 0.05$) between the treatments. Olsen P also had no significant difference, most of the treatments were within the range of 23.02 mg kg^{-1} (G2L1) to 9.90 mg kg^{-1} (G1L1) apart from 30.72 mg kg^{-1} (G1F1) (Figure 3.3c). Nitrate in the soil varied from 66.43 mg kg^{-1} (F1) to 1.84 mg kg^{-1} (G2L1F1), with no significant difference, except for concentrations of 1077.62 mg kg^{-1} (G1L1F1) and 104.34 mg kg^{-1} (L1), these were removed from analysis due to contamination (Figure 3.3b). Figure 3.3d shows that organic matter was between 1.00% (G1L1F1) and 1.98% (G1L1) for all of the treatments, G2L1F1 was the only treatment significantly different to the other ($p > 0.05$).

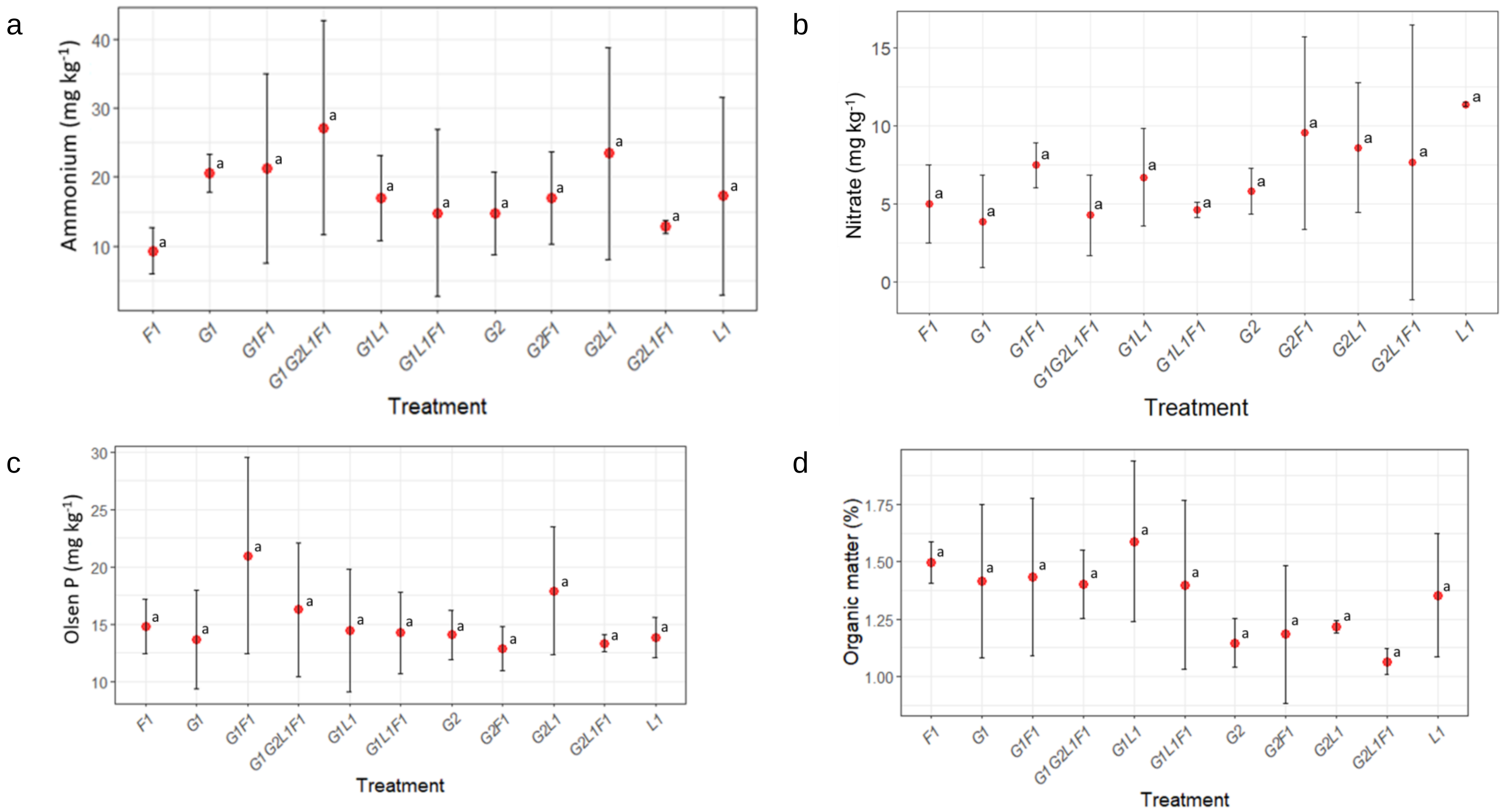


Figure 3.3: Ammonium (a), nitrate (b), Olsen P (c) and organic matter (d) of the soil after the biomass was collected arranged on the x axis by treatment. The bars represent standard deviation.

(M. sativa) had a significantly lower mean C:N ratio ($p < 0.05$) than the other species (except Grass) at 9.37 (Figure 3.4a). Both alfalfa (*M. sativa)* (0.46 mg g^{-1}) and the weeds (0.36 mg g^{-1}) had significantly more plant N than the other species (Figure 3.4b). The Levene test indicated that the variation between the species was significantly different for both the C:N ratio ($p < 0.05$) and plant N ($p < 0.05$). The Kruskal Wallis and Levene tests revealed no significant difference between the treatments for C:N ratio, plant N and C.

Alfalfa *(M. Sativa)* had significantly greater mean ($p < 0.05$) total plant C (162.2 mg) and N (18.0 mg) and, larger mean biomass (38.2 g) than the other treatments (Figure 3.5). Furthermore, there is significant ($p < 0.05$) variation between the species for total plant C, total plant N and biomass. When treatments were compared, G2L1 had significantly ($p < 0.05$) greater total plant N (20.1 mg) than the other treatments (Figure 3.5b). The Levene test indicates that the variations in plant N were significantly different between species, with weeds having a greater variation in plant N than the other species.

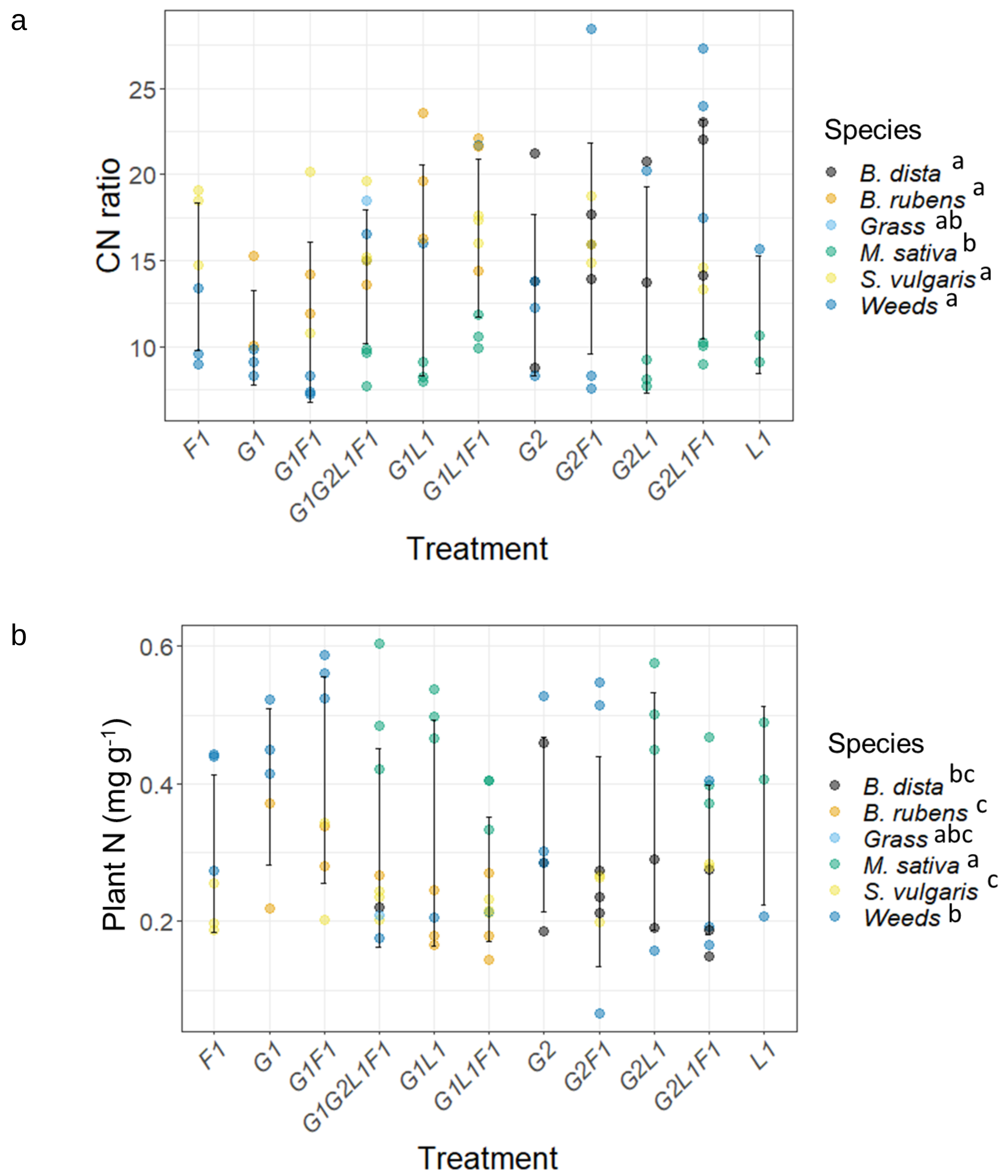


Figure 3.4: The C:N ratio (a) and plant nitrogen (b) separated into treatments along the x axis with the colour of the points representing the species in the treatment. The significant differences between the species are indicted with superscript letters in the key.

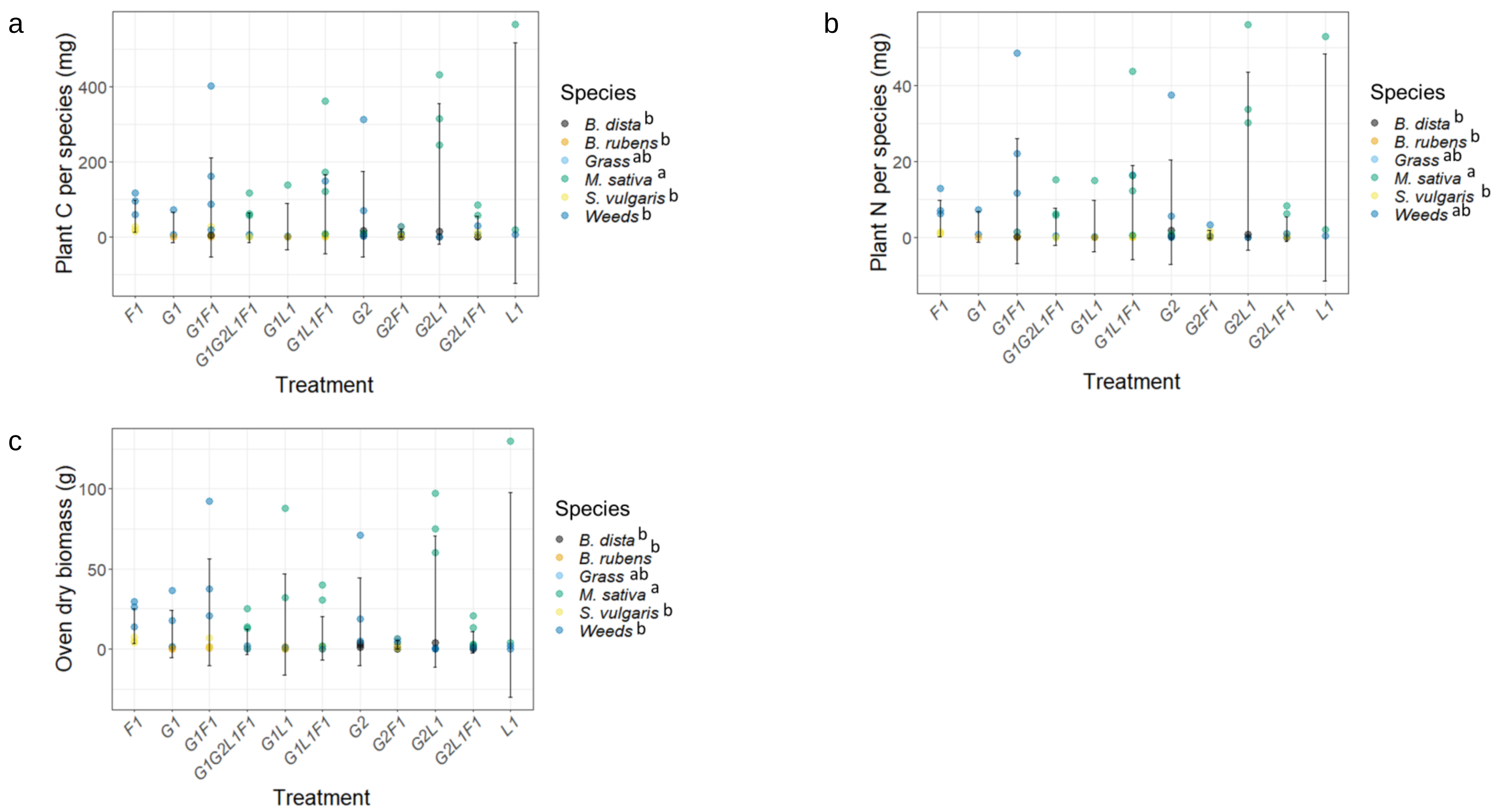


Figure 3.5 shows the total plant carbon (C) (a) and nitrogen (N) (b) and oven dried biomass (c) for each plant species, separated into treatments, and the colour of the points showing the plant. The significant differences between the species are indicted with superscript letters in the key.

3.4 Discussion

This chapter investigated the effect of cover crops, comprised of plants native to southern Spain, on soil and plant chemistry when planted in an olive orchard, and competition with spontaneous vegetation. To achieve this, soil samples were analysed for nitrate, ammonia, phosphorus, pH and organic matter. The oven-dried weight of the above ground biomass was recorded, and C and N analysis were conducted. While the legume, alfalfa (*M. sativa)*, contained more N than the other species and had the potential to create a nutrient rich litter, none of the treatments altered the soil chemistry significantly in comparison with the other treatments.

3.4.1 Short term impact of cover crops on soil chemistry

Table 3.2 and Figure 3.3c show that the Olsen P values of the soil prior to planting are close to those of the soil after the treatments were established, indicating that the cover crops did not deplete the soil P. These values are higher than the 5 to 15 mg kg^{-1} Olsen P values discovered by Rodrigues et al. (2015) in a rainfed olive orchard, in northeast Portugal. The ammonium and nitrate values of the soil after the cover crops had grown (Figure 3.3a and b) were significantly greater ($p < 0.05$) than the same soil before the treatments were planted (Table 3.2). Due to lack of access to the laboratory under COVID-19 restrictions, the extracts of the soil before planting were frozen at -18 ^{o}C for a year. The soil samples after harvesting were air dried and stored for several months before extracts were taken. This would have caused the samples to deteriorate (Bailey et al., 2022; Rhymes et al., 2021): Rhymes et al. (2021) found that nitrate in air dried soil (stored for 1 month) was 4.4 times higher than in soil extracted in the field. Rhymes et al. (2021) observed no significant change in ammonium concentration, however that again was in samples stored for one month, whereas the ones for this chapter were stored for longer. Although there is an overrepresentation of in-field nitrate, the values in Figure 3.3b, may be indicative of overall N availability due to the mineralisation and nitrification that occurred during sample storage (Rhymes et al., 2021). Furthermore, the samples were taken in different seasons which also impacts the nitrate and ammonium values in the soil (Bailey et al., 2022). Therefore, the difference in nitrate-N and ammonium-N in the soil due to the treatments is difficult to assess from the analysis conducted. The changes in ammonium and nitrate noted by Rodrigues et al. (2013) between legume cover crops and natural vegetation were 194.6 kg hm^{-2} and 7.1 kg hm^{-2}, with soil under legumes 28 times higher in N. However, this is smaller than the differences in ammonium and nitrate, which were 122 times and 44 times greater, respectively, in Figure 3.3a and b, than Table 3.2, further suggesting that the increases observed are not due to plant interactions alone.

There was no significant difference between the soil chemistry of the different treatments, indicating that no one treatment depleted or increased soil nutrients more than the other treatments. This is an important finding as it implies that the unfertilised cover crops are not diminishing the soil of nutrients, correlating with the findings of Rodrigues et al. (2015) who also found that cover crops, even after two years, did not cause any depletion of soil nutrients. However, as this study took place over six months it does not indicate whether annual use of these cover crops would result in any long-term change in the soil nutrient status. Also, there was no comparison with bare soil as there was no control treatment, so the planted treatments could not be compared with the rest of the field site. This was due to the impact of COVID and the changes to the methodology that had to be made once the field site had been set up. Despite the short-term period of this experiment, this result is reassuring for farmers concerned about nutrient competition (Gucci et al., 2012).

While the hypothesis that the leguminous mixes would increase N in the soil was proved incorrect (Figure 3.3), this may be due to the removal of above ground biomass from the field which did not allow the mineralisation of *M. sativa* in the soil (Rodrigues et al., 2015). Furthermore, the most prevalent weed in the field site was alfalfa (*M. sativa),* which, as a legume, may have conditioned the soil over previous seasons. Fox et al. (2020) found that after three years plant species identity had a highly significant impact on soil fungi and bacteria. Therefore, naturally occurring alfalfa (*M. sativa)* may be partially responsible for the lack of significant difference in the nitrate and ammonium between the treatments, as the soil conditioning influences subsequent crops (Baxendale et al., 2014; Fox et al., 2020). As legumes have a dominant species identity (Schmidtke et al., 2010), sometimes referred to a “keystone plant species”

(Spehn et al., 2002), it is unsurprising that the biomass of alfalfa (*M. sativa)* is particularly high in the treatments where this species was planted as there was no way to differentiate between planted and naturally growing alfalfa (*M. sativa)*.

3.4.2 Potential longer-term impact of cover crops on soil chemistry

Above ground, the plant chemistry was only statistically significantly different for the legume, alfalfa (*M. sativa)*, which had significantly ($p < 0.05$) higher plant N (of 0.46 mg g^{-1}) than the other species (Figure 3.4b). As explained in section 3.4.1, this species was the most widespread weed in the field, which explains the high plant N content of the weeds (0.36 mg g^{-1}) in Figures 3.4b and 3.5b. These results are to be expected for a legume. Sainju et al. (2005) observed significantly higher N concentration in vetch biomass (19.5 mg g^{-1}) than in rye (4.1 mg g^{-1}) or weeds (16.8 mg g^{-1}). This confirms the findings of Peoples et al. (1995) that legumes contain more N in their leaves than other types of plants.

Legumes are frequently used as part of cover crop experiments (e.g. Rodrigues et al., 2015; Sastre et al., 2017; Cerdà et al., 2018). Kulmatiski et al. (2012) reported that legumes facilitated the growth of non N fixing plants, but their models showed that as the N in the soil increased the legumes were out competed which may limit the long-term benefits of the low Carbon:Nitrogen (C:N) ratio and plant N (Figure 3.4). However, legumes have been used in cover crops to provide N to cash crops: 121 kg ha^{-1} yr^{-1} N from hairy vetch cover crop taken up by red peppers (Lee et al., 2014). Additionally,220 kg ha^{-1} and 175 kg ha^{-1} of N, were taken up by cotton and sorghum, respectively, after a vetch cover crop (Sainju et al., 2005). Much lower figures were observed of N transfer from legume cover crops to grape vines (12-15 kg ha^{-1}); this was less than 10% of the N provided by the legumes but may have been due to the short duration of the study (Ovalle et al., 2010). Although figures were not provided, the transfer of N from legumes to tree crops were reported by Buresh and Tian (1997) and Craswell et al. (1997). Therefore, the above and below ground remnants of the cover crops in Figure 3.5 have the potential to transfer N to the olive trees. Furthermore, none of the above ground biomass of the sown cover crops had begun to senesce at the time of collection in April. This is advantageous as, despite sowing in October, the early senescence of a legume in the autumn was found to be of less benefit to the tree crop in a study by Rodrigues et al. (2013) as much of the N was leached during autumn rains.

The significantly lower C:N ratio for the legume (*M. sativa*) than the other species (Figure 3.4a) is confirmed by Rodrigues et al. (2013) who observed a C:N ratio of 20.4 for vetches but a ratio of 52 for unfertilised natural vegetation. A C:N ratio of less than 30:1 is the “theoretical mineralisation threshold” (Parr et al., 2014), indicating that all of the species used in this study would release the N in their tissues back to the soil for other plants, including tree crops, to utilise (Figure 3.4) (Lee et al., 2014; Sainju et al., 2005). The high plant N and low C:N ratio of the legumes (Figure 3.4a and b) is an important result as the N fixing properties of legumes can be used to support other plants (Lee et al., 2014; Liebman et al., 2018). This result suggests that if the above ground biomass is left to decompose in the field after it is killed in the summer, the plant litter could increase the nutrient levels of the soil, with the potential to benefit future cover crops or the tree crops (Buresh and Tian, 1997; Craswell et al., 1997; Rodrigues et al., 2015). It is normal practice for cover crops, where they are used, to be killed annually in semi-arid orchards in Spain (e.g. Raya et al., 2006; Francia Martínez et al., 2006; García-Ruiz, 2010; Gómez et al., 2018). However, the benefits of mulch, such as nutrient provision, are rarely considered: only Francia Martinez et al. (2006) and Raya et al. (2006) discussed the potential advantages of the mulch from annual plants. An additional benefit of using cover crops and leaving the plant litter on the surface is decreased evaporation from the soil, also preventing soil erosion and hosting natural predators (e.g. Yang et al., 2019; Bodner et al., 2007).

3.5 Conclusions

This study is important as it indicates that cover crops can grow well without the use of fertilisers. Furthermore, when compared to the Olsen P values of samples taken before the cover crops were planted, there is no decrease in soil nutrients. This ndicates that these cover crops do not deplete the soil of nutrients over the time of the study. While the nitrate and ammonium concentrations show an increase after the treatments were planted, this is likely to be due to the degradation of the samples. The mix of leguminous (alfalfa, *M. sativa*) and non-leguminous (false broom,*B. dista,* red broom*, B. rubens* and bladder campion *S. vulgaris*) species and the low C:N ratio could mean that after a couple of years of this treatment, the olive trees may benefit from additional N and C (Rodrigues et al., 2015; Rodrigues et al., 2013). Additionally, the combination of the traits provided by these planted species (large above ground biomass, tillering, tap roots and fine roots) are likely to control soil erosion and reduce runoff.

Ideally, the next step to pursue this line of enquiry would be to establish a long running field trial with different cover crop treatments, with legumes and without, to observe the long-term impacts of the legumes on the soil nutrients and whether the tree crops can benefit from them. As was seen during field work, *M. sativa* was naturally occurring at the field site. Thereforefor this farm the seeding of a leguminous cover species would not be required but the use of false broom (*B. dista),* red broom *(B. rubens)* and bladder campion (*S. vulgaris)* may further help to reduce soil loss – which is explored in Chapter 4.

4. A mesocosm experiment to assess the impact of different vegetation types as erosion control cover crops

4.1 Introduction

Soil degradation is a global issue affecting 40% of agricultural land, resulting in the loss of its fertility and costing approximately US$ 500 billion annually (García-Díaz et al., 2017; Pacheco et al., 2018). Within the European Union (EU), it is estimated that 60-70% of soils are degraded due to unsustainable management, contamination and soil sealing (due to rainfall) at a cost of €50 billion per year (EC, 2020).Furthermore, 24% of EU land is impacted by unsustainable water erosion rates and 12% of the area is affected by soil loss greater than 5 t ha^{-1} annually (EC, 2020; Wuepper, 2020). Tolerable rates of soil loss depend on rate of soil formation but an average in the Mediterranean is approximately 1.4 t ha^{-1} yr^{-1} (Verheijen et al., 2009). Since 2010 improved farming practices have decreased soil erosion in 20 EU member states, however, in Italy, Spain and Greece soil erosion has increased (Panagos et al., 2020; Wuepper, 2020). In Spain alone, 13% of agricultural land is at risk of severe to very severe soil erosion, with an additional 34% at a medium risk of soil loss (Repullo-Ruibérriz de Torres et al., 2018; Panagos et al., 2015). This vulnerability to soil erosion is due to the semi-arid environment and land management practices. Hot, dry summers result in sparse vegetation which provide little protection for the soil during intense autumn and winter rainfall (Moreno-de-las-Heras et al., 2020; Cantón et al., 2011). The intense rainfall on unprotected soil leads to splash erosion, runoff generation and gully formation (Poesen et al., 2003; SSSA, 2008). The water erosion is exacerbated by land management practices such as removing ground cover from between tree crops (Sastre et al., 2020).

Plant cover controls soil erosion as plant canopies absorb the KE associated with the impact of raindrops, decreasing splash erosion (Morgan, 2005)Plant stems, low lying leaves and plant litter impede and slow runoff, through increased friction, allowing sediment to deposit and infiltration to occur, resulting in reduced erosivity (Martínez-Murillo et al., 2013; Morgan, 2005; Zuazo et al., 2009). Roots reduce soil detachment by forming soil aggregates and anchoring the soil against overland flow (De Baets et al., 2008; Gyssels and Poesen, 2003). Over recent decades plant cover in Spanish hillside orchards has been systematically removed due to concerns about water and nutrient competition, and cultural perceptions of cleanliness (Sastre et al., 2020; García-Díaz et al., 2017). This practice has worsened soil erosion in these regions (Vanwalleghem et al., 2011) and prompted a surge in research to assess the ability of plant cover to control soil loss. Grasses are frequently used in cover crop studies: false broom (*Brachypodium distachyon)* has been researched in a vineyard (Ruiz-Colmenero et al., 2013), and an olive orchard (Sastre et al., 2016), resulting in an 87% and 80% reduction in soil loss relative to conventional tillage, respectively. However, in an olive orchard, another grass species, Italian ryegrass (*Lolium multiflorum)*, caused a smaller decrease in soil loss of 26%, compared to conventional tillage (Gómez et al., 2018). Other plant functional types have also been explored: in an almond orchard, thyme reduced soil loss and runoff by 97% and 91%, respectively, when compared to bare soil (Raya et al., 2006). However, both Raya et al. (2006) and Sastre et al. (2016) reported that legumes reduced soil loss less effectively than grass plots. This is due to the relatively sparse and brittle nature of the studied legumes (lentils (*Lens esculenta*), sainfoin (*Onobrychis viciifolia*) and bitter vetch (*Vicia ervilia*)) compared to the grasses studied (barley (*Hordeum vulgare*) and purple false broom (*Brachypodium distachyon*)) (Raya et al., 2006; Sastre et al., 2016) Nevertheless, despite these variations, it is clear that plant cover decreases soil loss when compared to bare soil plots; furthermore, cover, as plants, litter or chippings reduced soil loss and runoff by 96% and 98% relative to tilled and herbicide treated plots, respectively, in an apricot orchard (Keesstra et al., 2016). Plant mixtures as cover crops can be more effective at controlling erosion than monocultures due to increased ground cover (Soriano et al., 2016); and more diverse root traits enhancing soil aggregate stability (Pohl et al., 2009; Gould et al., 2016). Despite these studies showing that plant cover reduces soil loss there has been little uptake in the practice by the farming community, partially due to worries over water competition (Taguas and Gómez, 2015; Sastre et al., 2016). Some experiments (e.g. Gómez, 2005; Castro, 2004) have shown that cover crops increase water stress in tree crops. However, Sastre et al. (2020) observed that all the olive trees in their plots suffered from water stress but there was lower stress under false broom (*Brachypodium* *distachyon)* (3.0 MPa) and bitter vetch *Vicia ervilia* (3.1 MPa) treatments than the conventional tillage control (3.4 MPa), while spontaneous vegetation was associated with slightly higher water stress (3.5 MPa). Many field experiments record soil loss and runoff caused by rainfall over a long timescale, but rainfall simulation allows the effect of controlled rainfall on a localised area to be measured and accurately repeated (Martínez-Murillo et al., 2013; García-Díaz et al., 2017). Rainfall simulation to assess soil erosion has increased in popularity since the late 1990s (Iserloh et al., 2013) due to the precision, and replicability it provides in comparing the runoff and soil loss under different soil conditions (Jordan and Martinez-Zavala, 2008). Careful consideration of water quality, temperature and soil physical factors are needed before rainfall simulation data can be used in a model. Also, it is not possible to extrapolate the data to larger area, despite this, rainfall simulation provides useful comparative data (Iserloh et al., 2013; Repullo-Ruibérriz de Torres et al., 2018). Rainfall simulation assessment of soil loss has been carried out in-field in apricots (Keesstra et al., 2016), vineyards (García-Díaz et al., 2017), olives (Repullo-Ruibérriz de Torres et al., 2018) and in laboratories (Montenegro et al., 2013).

Many of the plants used in previous experiments in Spain are maintained throughout the year (e.g. Sastre et al., 2016; Ruiz-Colmenero et al., 2013). However, these species may be more difficult for farmers to manage due to the preferred practice to remove ground cover before the dry summer (Gómez et al., 2018; García-Ruiz, 2010). Financial and time constraints of farmers have limited the research into the use of plant mixes to control soil erosion in Spain, as the use of cover crops is perceived as more demanding than other methods (Gomez et al.,2018). However plant mixes could provide increased soil protection thus requiring further research to determine their suitability as cover crops in hillside orchards in Spain (Gómez et al., 2018). Additionally, plant traits are under researched in soil erosion studies. Few rainfall simulation experiments have compared different plant species to provide detailed insight into the comparative effectiveness of various plants (Repullo-Ruibérriz de Torres et al., 2018; De Baets et al., 2009).

This chapter gives an overview of rainfall simulation carried out on mesocosms in a polytunnel. Above and below ground plant traits are considered to provide insight into the utility of the monocultures and plant mixes to control soil erosion. The research question for this chapter was: which traits are associated with reduced soil loss and runoff? The objective of this paper is to determine whether vegetated plots produce less soil loss and runoff than bare plots under simulated rainfall, and whether there is a difference between the vegetated treatments used. Above ground biomass, soil cover, below ground biomass and root diameter were measured to identify the impact of these traits on soil erosion.. It was hypothesised that the mixed vegetated treatment will produce less runoff and soil loss than the monocultures. This is due to the mixture of complementary plant traits expected to be present in the mix based on previous chapters.

4.2 Methods

4.2.1 Mesocosm set up

Plant species native to Spain which have been previously used as cover crops (e.g. Gómez et al., 2018) were selected for this experiment. One grass, one legume, one forb species and a mixture of the three were planted as cover for mesocosms. The species were chosen based on their traits, which based on Chapter 2 would provide a good mixture of above and below protection from rainfall and overland flow. Only one mixture was tested due to limited space in the polytunnel.

Table 4.1: The species and treatments used in the mesocosm experiment.

Treatment ID	Species planted	Seeding rate
Bare	No planting	N/A
Grass	False broom *(Brachypodium distachyon)*	6 g m^{-1}
Legume	Alfalfa *(Medicago sativa)*	3 g m^{-1}
Forb	Bladder campion (*Silene vulgaris)*	3 g m^{-1}
Mix	False broom *(Brachypodium distachyon),* alfalfa *(Medicago sativa)* and bladder campion (*Silene vulgaris)*	3, 1 and 1 g m^{-1} repsectively

The mesocosm trial was conducted in a polytunnel at Hazelrigg Field Station at Lancaster University. It consisted of 23 plots, three were bare and five replicates of each vegetation treatment. The treatments were: false broom (*Brachypodium distachyon)*; alfalfa (*Medicago sativa)*; bladder campion (*Silene vulgaris)* and a mix (Table 4.1). This experiment took place between March 2021 and August 2021. Germinated plants (within one week of sprouting) were planted in the runoff boxes and grown for 10 weeks before runoff analysis. The temperature in the polytunnel fluctuated, this was not measured but external temperature varied from 10°C to 30°C. The seeds were purchased from Semillas Cantueso (Córdoba, Spain).

The mesocosms were made from plastic containers with an internal area of 55.5 cm x 36 cm x 11.5 cm (Euro Container ref. 9230001, Schoeller Allibert Ltd, UK) (see Figures 4.1 and 4.2). The base of each container was attached to plywood to provide reinforcement and drainage holes were drilled through both the container base and the plywood. The front edge was cut down by 2.5 cm to ensure that the soil was flush with the lip of the container. The removed section was temporarily re-attached until the runoff analysis started. The guttering attached to this lip was made from semi-circular pipe of 40 mm diameter with a 90° elbow at one end to facilitate the collection of runoff. Silicone was used to seal joints and prevent leakage.

The soil used was a loamy sand (sand 87%, silt 9% and clay 3%) Norfolk topsoil (pre-screened to 20 mm) ordered from Bailey's of Norfolk. The mean pH of the soil was 7.59. Mean ammonium, nitrate and phosphorus concentrations were 0.003 mg kg^{-1}, 0.775 mg kg^{-1}, and 2.628 mg kg^{-1}, respectively. The organic matter content of the soil was a mean of 3.06%. This soil was selected for its similarity to Spanish soils which have low organic matter (<2%) (Ferreira et al., 2022), also loams (clay to sand) are common in Spain (García-Díaz et al., 2017). The olive orchard where Chapter 3 took place had a silty clay soil texture. However, the aim of this chapter was not to replicate the conditions of Chapter 3 but to attempt to use "average" Spanish conditions. The methods used to determine the soil physical and chemical properties are the same as those used in Chapter 3. The boxes where uniformly packed with soil to the lip of the cut down section of the box. The soil was watered and left for a couple of days to settle, then filled to the lip once again. Then the germinating seeds were planted into the box.

4.2.1.1 Runoff experiment

A rainfall simulator (Figure 4.1) was constructed using a Fulljet B3/8HH-9.3 nozzle and attached to a hose pipe. This was attached to a metal pole along with a pressure gauge and a circular rail holding a waterproof curtain. The rainfall intensity was 480 mm hr^{-1}, this was measured by collecting all of the rainfall falling in a mesocosm in one minute, three replicates were carried out and the mean was calculated. This rainfall intensity is very high, this was partially due to limited availability of equipment due to COVID. The nozzle used is usually connected to a computer to control the rainfall intensity, however, as this experiment took place in a polytunnel there was no way of connecting the nozzle to a computer with the correct software. The rainfall intensity was very high but this has been observed to occur naturally in Romania (>600 mm h^{-1}) and Germany (>750 mm h^{-1}) . Christiansen's uniformity coefficient was 72.3 and the pressure was maintained at 0.5 bar. The rainfall simulator was attached to the frame of the poly tunnel and moved over the centre of each box prior to analysis. Before each simulation the curtain was securely tucked around the sides of the box to prevent water falling on the neighbouring plots. It was ensured that no water dripped or ran from the curtain into the mesocosm. Each box was raised to a 10º angle, measured with a clinometer, and the raised end of the box was supported on wooden planks (Figure 4.2). The 10º angle was used because any orchards with a mean slope more than 6º in Spain are legally required to use soil cover, whether cover crops, mulch or pruning residue (Taguas and Gómez, 2015). This was increased to 10º in this experiment to account for the steeper part of sloping orchards with a 6º mean. Any gaps between the soil and the box were plugged using plumbers' putty, this was only needed on two mesocosms.

For each box, a bucket was placed under the rainfall simulator and the hose connected the water supply (Figure 4.2). The pressure gauge was checked to ensure that it was consistent (0.5 bar), then a timer was started as the bucket was removed. The time to runoff initiation was recorded. The runoff was collected in 5 litre buckets, the bucket was covered so only the runoff entered and not the rainfall. Every 5 minutes a subsample was taken, either for one minute duration or until roughly 500 ml was collected, the time to collect the subsample was recorded. The subsample volume was measured using a volumetric cylinder, recorded and poured into a tray to evaporate at ambient temperature. The quantity of the subsample and of additional water used to rinse sediment from the beaker and measuring cylinder was noted. Four subsamples were taken for each plot, after which the timer was stopped (rainfall duration was roughly the same for each plot but varied by a few seconds), and the bucket placed under the nozzle before the hose was disconnected. The total time of the simulation and total runoff (± 1 litre) was recorded.

Figure 4.1: A photograph of the mesocosm and rainfall simulator set up. There were two rows of boxes, the rainfall simulator was attached to the frame of the poly tunnel and the nozzle was positioned over the centre of each box before the simulation began.

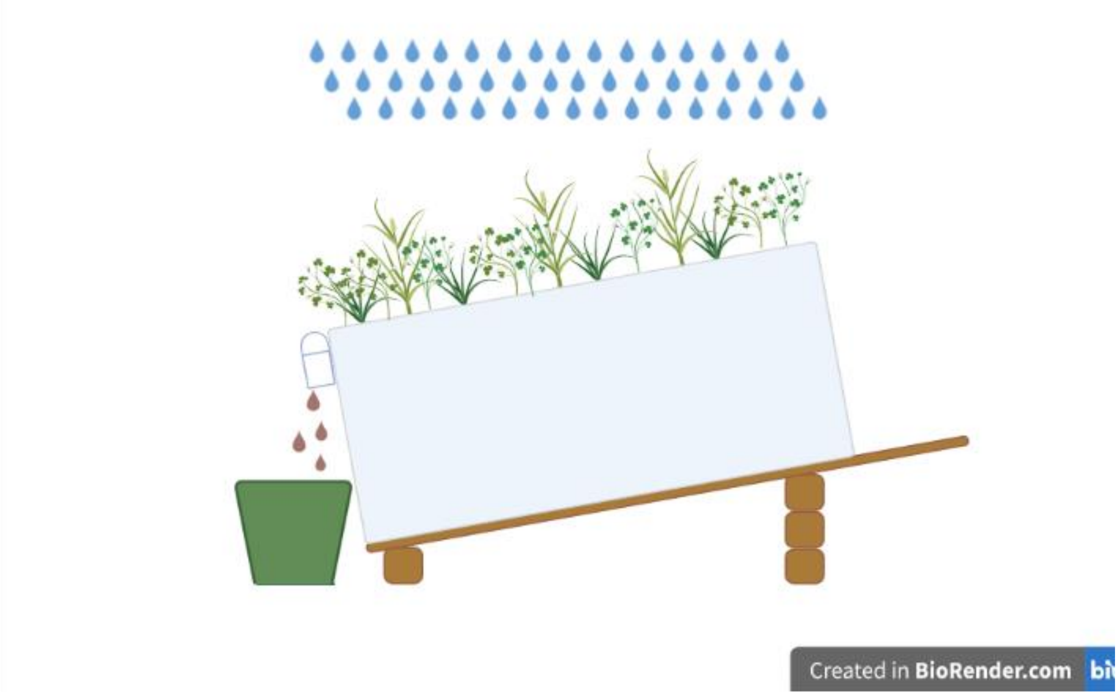


Figure 4.2: A diagram of the runoff experiment set up. The boxes were raised to a 10^o angle before the rainfall simulation started and runoff was collected in a bucket. The volume of timed subsamples was measured and left to evaporate before the sediment was weighed.

4.2.2 Laboratory analysis

After each rainfall simulation a photograph was taken of the plot and analysed to determine soil cover. Soil cover software was unable to differentiate between yellow and brown vegetation cover and soil, giving much lower soil cover percentages than were present. Therefore, in Microsoft Powerpoint a 10 x 10 table was overlaid on each photograph and the percentage of soil cover was calculated by eye.

The mass of the sediment was weighed, the trays had been pre-weighed before sediment was added so the tray plus sediment was weighed and the tray weight subtracted. Once the rainfall simulations were complete the biomass was collected from each plot and a 0.003 m^3 soil core was taken. The biomass was dried in an oven at 70 ^oC for 72 hours. The roots were removed from the soil core and washed; these were stored in 50% ethanol, 50% water in at 3-5^oC . The roots were scanned using an Epson Perfection V700 PHOTO, the scans were analysed using WinRHIZO 2009c software. The roots were thoroughly rinsed then dried in an oven at 70 °C for 72 hours before the dry weight was recorded.

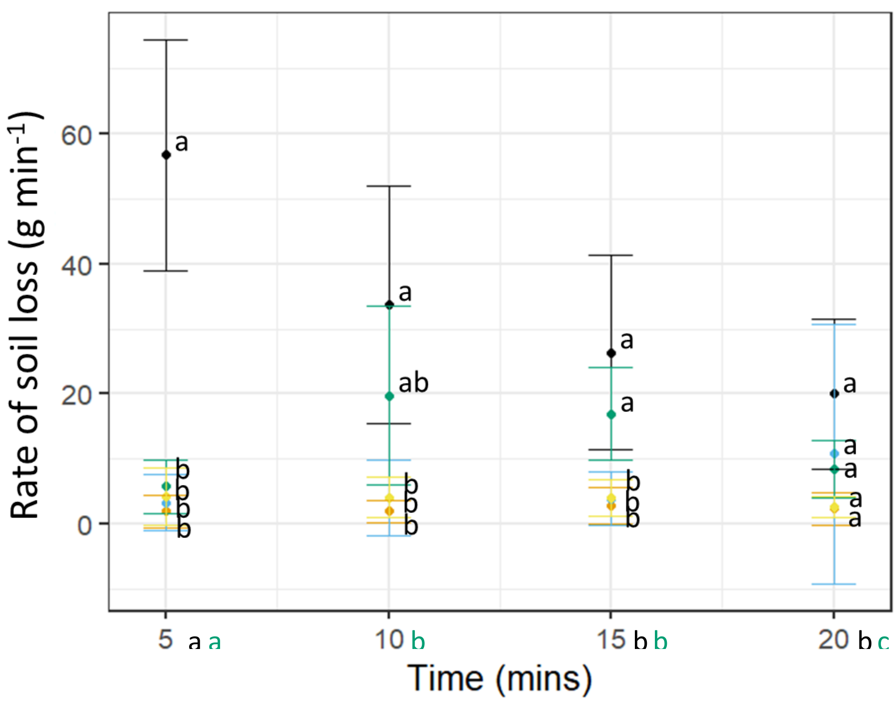
4.2.3 Data analysis

One way ANOVA and Kruskal Wallis analyses and Levene tests were conducted on each treatment for all parameters. A Tukey post-hoc test was also used. Paired parameters were plotted and analysed using Pearsons and Spearmans correlation coefficients. A two-way ANOVA was used for analysing the time series. The statistical analysis and graph production was performed using RStudio Version 1.3.1056.

4.3 Results

Soil loss from the bare plots (34 ± 20 g min^{-1}) was significantly higher ($p < 0.05$) than that from vegetated plots (6 ± 8 g min^{-1}) (Figure 4.3a). However, there was no significant difference in the volume of runoff between bare (1194 ± 88 ml min^{-1}) and vegetated plots (805 ± 251 ml min^{-1}) (Figure 4.3b). The vegetated plots are only grouped together for this comparison with the bare treatment. The rest of the results analyse the vegetated treatments separately.

a



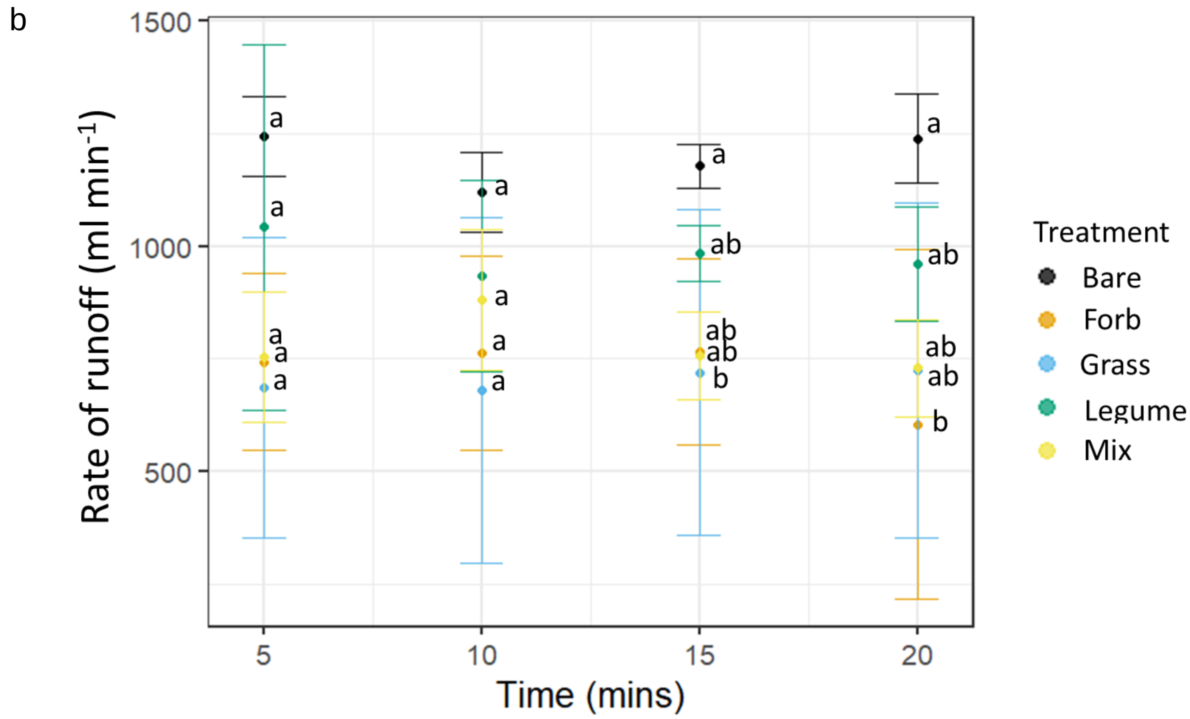


Figure 4.3: (a)the rate of soil loss and (b) rate of runoff. The mean of the subsamples and replicates is shown by the black dots and the error bars are ± 1 standard deviation.

There was a significant ($p < 0.001$) negative correlation ($r \leq -0.65$) between the above ground parameters (above ground biomass and cover) and runoff volume and soil loss (Figure 4.4). When the data from the bare plots was removed, this significant negative correlation remained with cover and runoff having the least negative correlation ($r = -0.46$, $p < 0.05$) and the most negative correlation between above ground biomass and runoff ($r = -0.70$, $p < 0.001$). The vegetated treatment with the lowest plant cover and above ground biomass was Legume (41 ± 13% and 61.70 ± 6.80 g, respectively), while the highest was Grass (86 ± 3% and 101.01 ± 15.64 g, respectively) (Figure 4.4). These treatments were significantly different for biomass and cover. However, Grass also had significantly greater cover than the mix, whereas the Legume had significantly less cover than the Forb as well as the Grass treatment. There was a significant ($p < 0.001$) positive correlation ($r = 0.69$) between the plant cover and above ground biomass.

None of the correlations between below ground parameters and runoff or soil loss were significant at $p < 0.05$ (Figure 4.5). The bare treatment had the lowest DW below ground biomass (0.02 ± 0.01 g), while Forb had the highest (0.65 ±

0.47 g) (Figure 4.5 a and c), these were significantly different. The largest mean root diameter was observed in Legume (0.30 ± 0.02 mm) and the smallest root diameter was recorded for Grass (0.20 ± 0.00 mm) (Figures 5 b and d). The Legume had significantly greater root diameter than the other treatments, Grass and Bare treatments had significantly smaller root diameter than the other treatments.

The highest rates of runoff and soil loss were observed in the bare plots (1194 ± 89 ml min^{-1} and 34 ± 20 g min^{-1}, respectively) (Figures 4.4 and 4.5). The soil loss from Bare plots was significantly higher than the other treatments. However, the Bare and Legume plots both had significantly higher runoff than the other treatments. The lowest mean rate of runoff was recorded for Grass (702 ± 333 ml min^{-1}) (not significantly lower than the Mix or Forb treatments). While the lowest mean rate of soil loss was observed in Forb (2 ± 2 g min^{-1}) (Figures 4.4 and 4.5) (this was significantly lower than all treatments except the Mix).

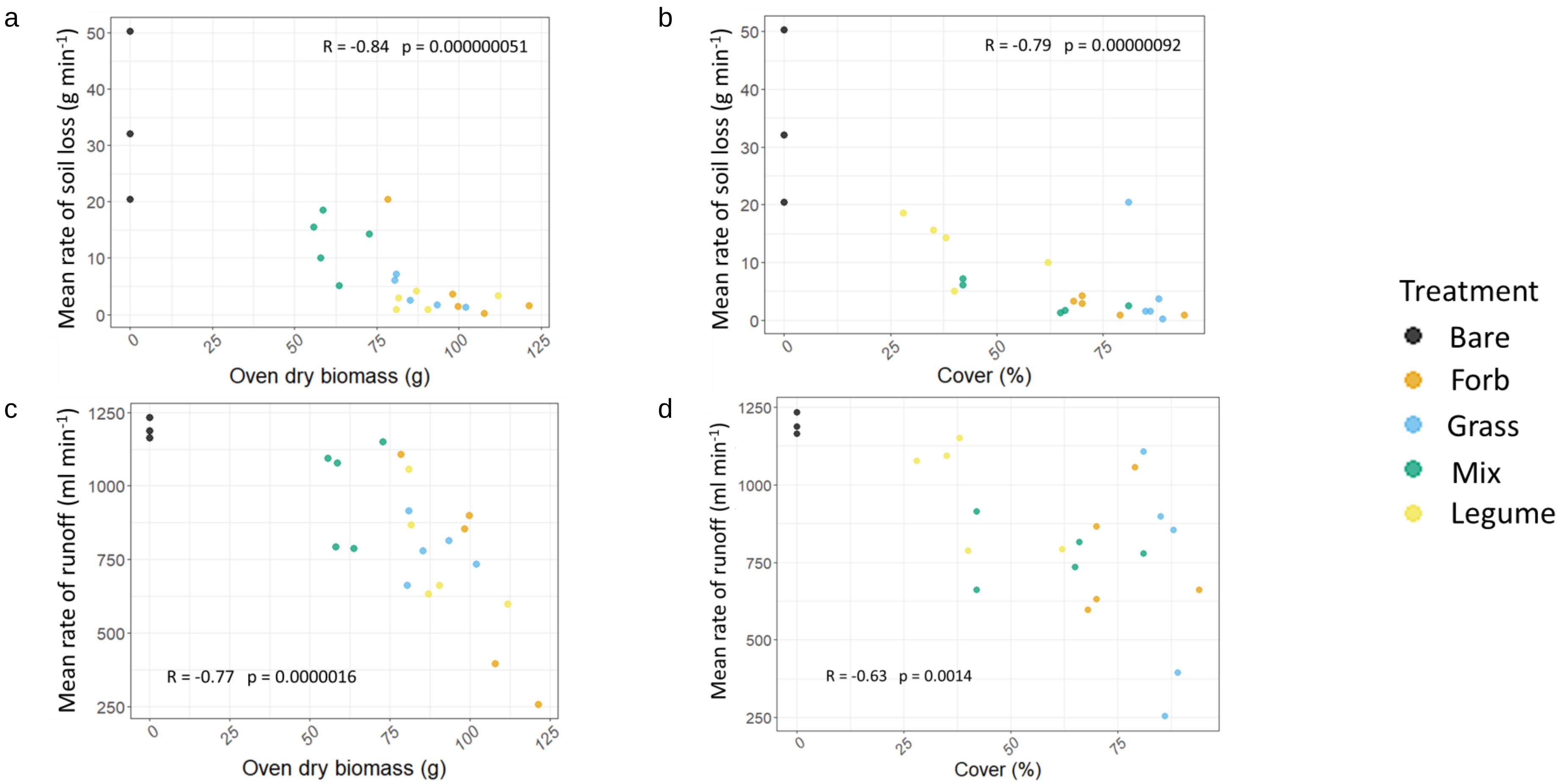


Figure 4.4 (a) indicates the relationship between soil loss and above ground biomass, (b) shows the impact of soil cover on the rate of soil loss, (c) illustrates the correlation between runoff and above ground biomass while (d) demonstrates the effect of cover on runoff

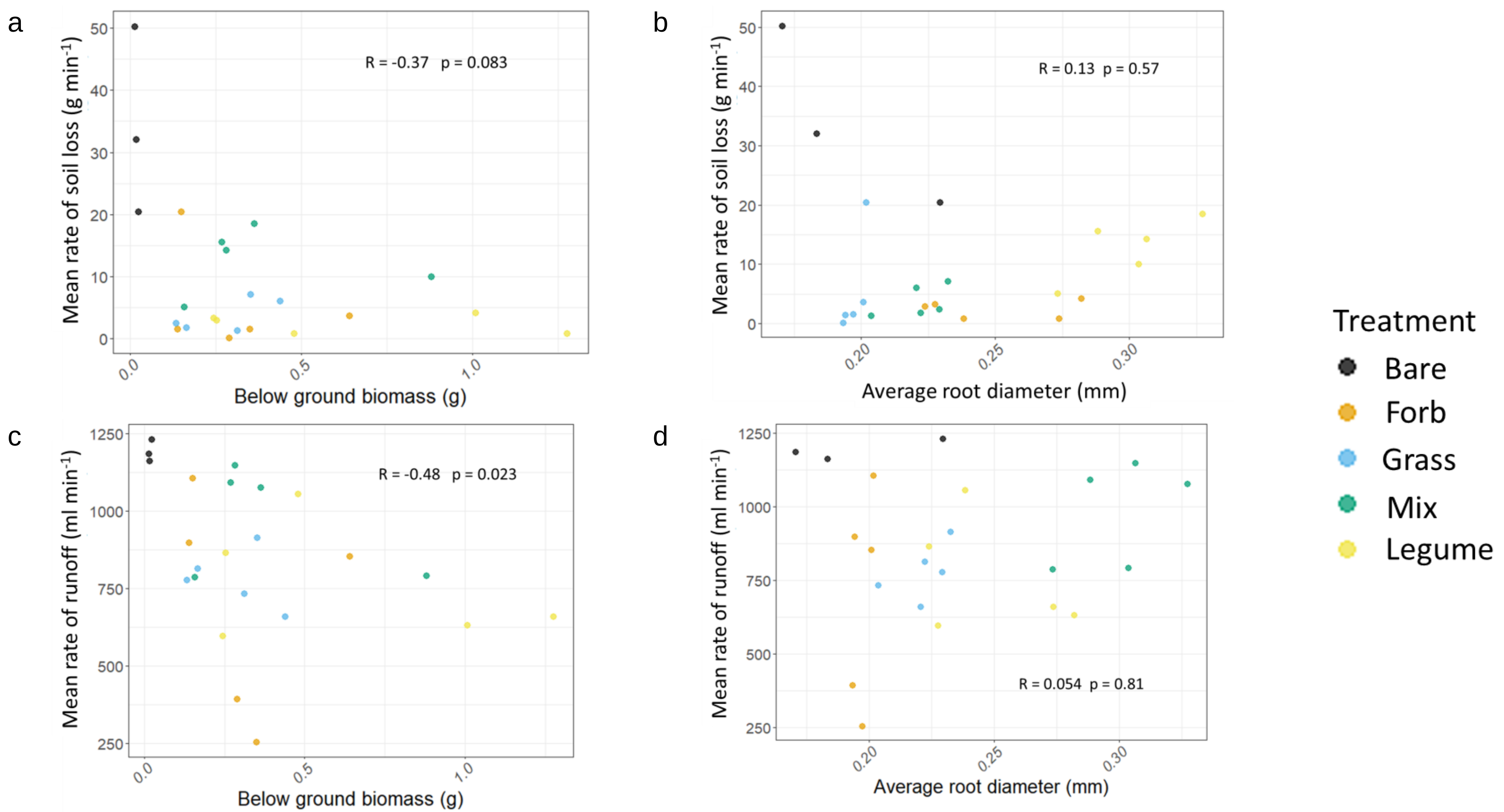


Figure 4.5 (a) demonstrates the correlation between below ground biomass and the rate of soil loss, (b) indicates the relationship between root diameter and soil loss, (c) shows the impact of below ground biomass on runoff and (d) illustrates the effect of root diameter on runoff.

4.4 Discussion

While it is well known that vegetated or covered plots generate less soil loss than bare plots (e.g. Keesstra et al., 2016; Sastre et al., 2016), the erosion control effectiveness varies with different vegetation types (Repullo-Ruibérriz de Torres et al., 2018). As expected, soil loss was significantly higher for the bare plots than the vegetated ones ($p < 0.05$) (Figure 4.3a). Although this is unsurprising it does reinforce the use of cover crops to prevent soil loss. When the rate of soil loss was separated by the subsamples taken every 5 minutes throughout the rainfall simulation (Figure 4.3a), more was understood about the different treatments. Unsurprisingly, the bare soil had significantly more soil loss than the vegetated treatments when the first subsample was taken. This was due to the movement of loose soil on the surface which was not protected by plant cover (Morgan, 2005). It is thought that smaller particles were moved at the start of the simulation, once these were washed out of the box the rate of soil loss slowed. This is why the rate of soil loss from the bare plots decreased (significantly lower soil loss at 15 and 20 minutes compared to 5 minutes) over time (Figure 4.3a). Whereas the rate of soil loss from the vegetated treatments was more consistent. However, the Legume treatments saw an increase in soil loss in the second subsample. By the third subsample (15 minutes), the Legume had significantly greater soil loss than the other vegetated treatments. This is expected as the lower erosion control properties of legumes has been widely documented (e.g. Raya et al., 2006; Sastre et al., 2016), but they have other benefits in terms of N-fixation which were not analysed in this chapter (see Chapter 3). For the last subsample there was no significant difference in soil loss for any of the treatments. This is likely to be due to the high rainfall intensity which resulted in greater movement of smaller soil particles from the Bare plots than would be expected under less intense rainfall (Abu-Zreig et al., 2003). The high degree of soil protection provided by Grass (the soil lost from Grass plots was 84% lower than that lost from Bare plots (Figure 4.3a)) was also observed by Ruiz-Colmenero et al., (2013) and Sastre et al., (2016)

There is a much less clear story when the rate of runoff is considered for each of the subsamples (Figure 4.3b). The Bare treatments had the highest mean runoff for each subsample, but, except for two instances, this was not significantly greater than the other treatments. At the third subsample at 15 minutes, the Bare treatments had significantly higher runoff than the Grass treatments. During the final subsample (20 minutes), the Bare treatments were significantly higher than the Forb treatments. Unlike for soil loss, there was no difference in runoff in the same species at different subsamples. Similar findings of lower impact on runoff than soil loss by cover crops were also reported by Raya et al., (2006), Bochet et al., (2006) and Repullo-Ruibérriz de Torres et al., (2018). Interestingly, the variation within the treatments was greater for runoff in the vegetated plots than soil loss. The opposite was recorded for the bare plots: there was a higher variation in soil loss than runoff. This may be due to differences in shoot density and plant litter between individual plots, which have an important impact on erosion control (De Baets et al., 2006; Zuazo et al., 2009), rather than between treatments. A theory proposed by Li and Pan (2018) states that the rainfall impact caused soil sealing in the bare plots which limited infiltration causing higher runoff than from grassed plots. However, no soil sealing was observed during the rainfall simulations.

The size of the plots and the short growing period within the mesocosms limited the influence of the vegetated treatments on earthworms, pore space connectivity and total pore space, all key factors in determining infiltration rate in the field (Ruiz-Colmenero et al., 2013; Keller et al., 2018). Furthermore, the limited space and nutrients of the mesocosm may have impacted the below ground development of the plants, more than the above ground development (Loades et al., 2010). Unlike the above ground parameters, there was no statistically significant correlation between the below ground parameters and soil loss or runoff (Figure 4.5). This was surprising as these species were chosen for traits such as fine roots which anchor soil at the surface, and tap roots which promote infiltration, thus reducing runoff. Therefore it was expected that the below ground parameters would correlate with soil loss and runoff. Also, despite regular weeding, roots were present in the Bare plots which could not be removed prior to rainfall simulation, therefore the sharp distinction between the bare and vegetated treatments for above ground parameters was missing below ground (Figures 4.4 and 4.5). Although grass roots have been found to be effective at reducing soil loss (Li and Pan, 2018), the Grass treatment did not have a significant impact (Figures 4.5a and b). However, above ground, the plants developed to maturity and had a clear impact on soil loss.

Above ground plants traits reduce soil loss and runoff due to the interception of raindrops by the canopy (Bochet et al., 2006) and vegetative carpeting to provide additional shielding for the soil (Raya et al., 2006). Plant height is important as the closer the plant canopy is to the soil the more effective protection it provides (Morgan, 2005); and litter production which slows runoff and traps sediment (Zuazo et al., 2009). Both above ground biomass (AGB) and soil cover were observed to have a significant ($p < 0.001$) negative correlation with soil loss and runoff (Figure 4.4). Runoff has a significant correlation despite no significant difference between the treatments when analysed with ANOVA, as the correlation analysis considered all data points, not just the means. Although all the treatments examined are represented in Figure 4.4, statistical analysis was also carried out with the bare plots removed to determine what affect this had on the relationship. Despite a decrease in the correlation it remained significant ($p < 0.05$), demonstrating the importance of differences between vegetation types on erosion control (Bardgett et al., 2014).

Although it was hoped that the mixed treatment would decrease soil erosion more effectively than the monocultures, Figure 4.3 indicates that there is no significant difference between the vegetated treatments. The combination of high root volume from false broom (*Brachypodium distachyon)*, fast infiltration in alfalfa (*Medicago sativa)*, and low height of bladder campion (*Silene vulgaris)* (Chapter 2) were predicted to increase erosion control due to the diversity of plant traits (Zhu et al., 2015). Nevertheless, the mix had significantly lower soil loss than the bare plots ($p < 0.05$) and the mix could provide nutritional benefits as discussed in Chapter 3.

4.5 Conclusions

The connection between soil loss and vegetation cover has been confirmed by the findings of this rainfall simulation as a significant difference was observed between the soil loss from bare and vegetated plots. While the relationship between runoff and vegetation types was not significant, this is not unusual (e.g.

Bochet et al., 2006). The mixed vegetated treatment had less impact than expected, as it was not significantly different that the other vegetated treatments for any of the above or below ground parameters, neither did the mix produce the least soil loss or runoff (Figure 4.3).

In this experiment above ground parameters (Figure 4.4) had more of an impact on runoff and soil loss than below ground parameters (Figure 4.5). This may be due to the short growing time, seedlings were planted in the mesocosms 11 weeks before rainfall simulation, or the limited below ground area for root growth (Loades et al., 2010). However, this is an important finding as many tree crop farmers in Spain are worried about water and nutrient competition in the summer months and remove ground cover, whether planted or spontaneous, allowing only a small window during the autumn and winter for the cover crops to develop (Taguas and Gómez, 2015). The behaviour and views of Spanish farmers are examined in Chapter 5. However, the outcomes of this chapter suggest that above ground traits of cover crops may be the most important consideration. Nevertheless, extrapolating rainfall simulation or mesocosm data to predict in-field impact is risky (Martínez-Murillo et al., 2013). Therefore, a field trial investigating the role of above and below ground plant traits on controlling erosion in a field setting would be ideal.

5. Farmer perceptions and management of soil erosion in tree crops in Spain

5.1 Introduction

The need for, and effectiveness of, plant cover to control soil erosion has been highlighted and examined throughout this thesis. Use of cover crops to control soil erosion in hillside orchards has increased in Spain in recent years, approximately 60% of farmers use cover crops, however this uptake varies by region and tree crop (Gómez et al., 2021). There are numerous barriers that farmers face to transition from traditional use of tillage and herbicide to keep soils bare, to the use of vegetation cover (Vanwalleghem et al., 2011). These barriers include concerns about competition with tree crops, finances and strong ties to traditional practices (Keesstra et al., 2019; Calatrava and Franco, 2011).

Water competition with tree crops and the impact on yield is a source of concern for farmers when implementing changes to land management. Although the use of cover crops with specific plant traits can result in an increase in soil water (Basche and DeLonge, 2017; Ruiz-Colmenero et al., 2013). The tree crops growing in Spain are adapted to the climate and low water availability. Nevertheless, the need for large yields (3205 kg ha^{-1} yr^{-1} of olives in Andalucía alone in 2010, a 430% increase from 1900) have led to fierce protection of water resources for trees (García-Ruiz et al., 2011). The impact of competition for water and nutrients between cover crops and tree crops varies between studies. Gucci et al. (2012) observed a 65% decrease in olive fruit yield from crops under a permanent natural cover. However, long-term cover crop treatments were found to offset the effects of rainfall variability in arid environments, through reducing evaporation of water from the soil surface, and facilitating the replenishment of ground water storage (Basche and DeLonge, 2017). Furthermore, both long-term no-till and seasonal cover crops improved soil structure and slightly increased soil water conductivity and storage (Araya et al., 2022). In other seasonal trials, where the vegetative cover was killed in spring, the impact of cover crops on soil water is positive, with greater soil moisture observed under plant cover than no-till plots by Zuazo et al. (2009) and Keesstra et al., (2016).

Although water is the primary limiting factor, nutrient competition is another concern for orchard farmers, particularly as soil erosion causes the soil to become less productive (Gómez et al., 2018).

Vegetation cover, including cover crops, have an impact on soil chemistry and microbial communities, however, similar to water this effect is mixed (Fernandez et al., 2016; Cardinali et al., 2014). Sastre et al. (2020) observed a significant olive yield decrease under a permanent false broom (*Brachypodium distachyon)* cover due to N competition. However there was no significant impact of the other ground covers examined: permanent spontaneous vegetation and annual bitter vetch (*Vicia ervilia)*. Leguminous cover crops can increase the nitrogen content of the soil due to the biological N-fixation resulting from a symbiotic interaction with rhizobial bacteria (Peoples et al., 1995). Isotope analysis has shown that the amount of N delivered from legume cover crops to tree crops rivals that of N fertiliser (Ovalle et al., 2010; Snoeck et al., 2000).However, autumn senescence of legumes in the Mediterranean reduces the transfer of N to crop trees due to the heavy rainfall resulting in leaching in that season (Rodrigues et al., 2013). This reduction does not offset the benefit of the legumes, particularly when the plants die in spring, when the N concentration in crop trees in legume plots is higher than those with N fertiliser (Rodrigues et al., 2013).

The financial impact of potential loss of yield caused by water and nutrient competition is a hurdle for farmers. As much of a barrier is the soil management tradition of removing vegetation which has become culturally ingrained and is hard to alter (Sastre et al., 2016). Spontaneous vegetation is also routinely removed and farmers who leave “weeds” or plant cover crops are considered to be exhibiting bad management, and thought of as dirty and lazy (Keesstra et al., 2019). Some farmers have suggested that financial recompense for their loss of reputation would encourage them to try cover crops (Cerdà and Rodrigo-Comino, 2021). However, in the literature that explores farmers perspectives, there is little mention of whether the respondents are aware that cover crops may not have the negative impacts farmers believe they do, or what the potential benefits of cover crops are. Although recent Spanish policy changes (e.g. a requirement to have soil cover on slopes above 10%) indicate that the policy makers know about some of the cover crop research (Taguas and Gómez, 2015), the slow uptake of cover crops suggests that the information may not be reaching farmers.

This chapter addresses the research question: how do farmers deal with soil erosion and is there a communication barrier between farmers and researchers in Spain? It was hypothesised that the farmers who answered the questionnaire would use, or have used, cover crops, but they would have had a variety of experiences. A further hypothesis was that farmers were not aware of the academic research conducted.

5.2 Methods

An online survey and in-person interviews were used to collect data for this chapter. The Ethics Committee of the Faculty of Science and Technology at Lancaster University approved the process.

The survey was composed of 25 questions, split into sections on: the farm, soil and water conservation methods, cover crops, and comparing soil and water conservation methods (Appendix 1). Spanish colleagues checked translation of the survey into Spanish. The surveys were constructed, distributed and analysed using Qualtics. A link to the survey was sent to colleagues and industrial partners, primarily from CSIC and Primafruit, who circulated it to all suitable farmers in their network. The survey was fully completed by 27 farmers (Figure 5.1). An online survey was chosen as it could be completed quickly and remotely by farmers. This was sent out while COVID-19 restrictions were in place and it was not possible to travel to complete in-person data collection. The survey was semi-structured and respondents were given opportunities and encouraged to write long answers. However, there was no opportunity for follow up questions. Depending on restrictions once the survey was complete, either online or in-person interviews were planned with a smaller group of farmers. The latter was possible.

The interviews were organised through Primafruit and were carried out on farms in Valencia, four interviews took place. The objective of the interviews was to delve more deeply into some of the questions and to ask questions raised by the survey. Each consisted of 30 to 40 minutes of semi-structured interview, and a tour of the farm. The interviews were composed of 34 questions with sections on the interviewee, soil erosion, cover crops, water, nutrients and cost (Appendix 2). The interviews were conducted with a translator, who translated a summary into English at regular intervals and relayed additional questions to the farmer. Recordings of the interviews were transcribed in Spanish and translated word-for-word into English. Frequency analysis was used on the transcribed interviews, whereby searches were conducted within the transcripts key words to determine the frequency of use.

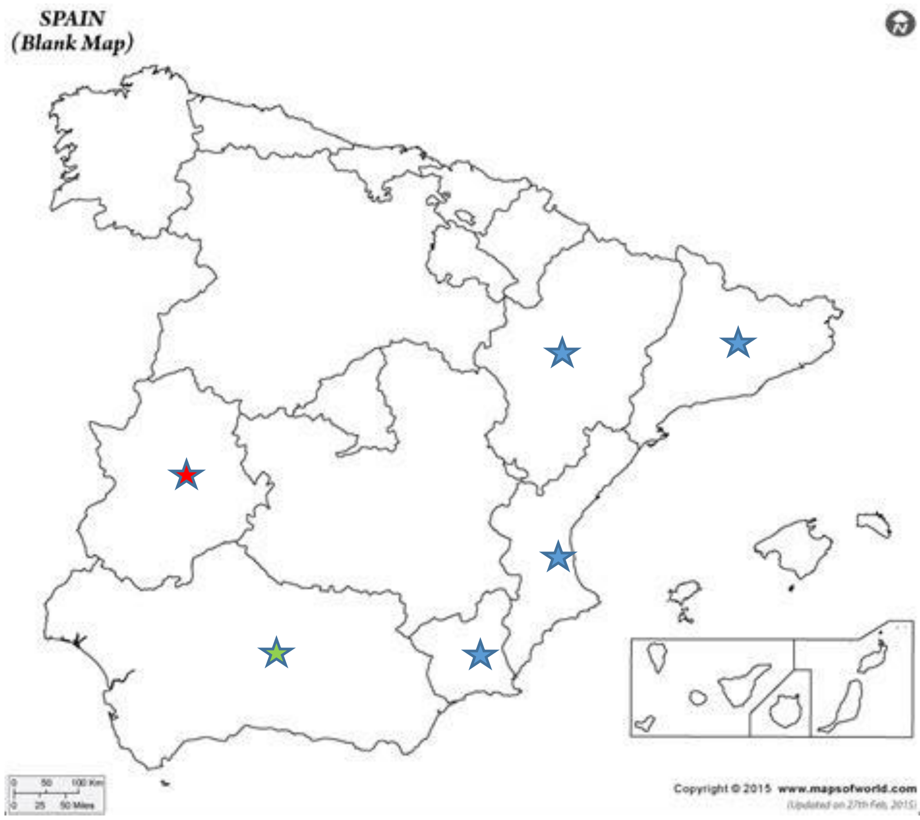


Figure 5.1: The locations of the autonomous regions of Spain where farmers completing the survey were located. Three responses came from Extremadura (red star) and twenty from Andalucía (green star). The blue stars all represent one response. The blank map was obtained from http://getdrawings.com/images/spain-map-drawing-2.jpg on 06/12/21.

As the survey was sent the farmers via researchers and a supermarket supplier requiring high standards, the farmers reached were more likely to have participated in research and considered sustainability more than the general farming population. The privacy of the respondents was a priority, and they were assured that no-one other than the primary researchers would see the data before anonymisation. However, the respondents may have been less forthcoming, or unwilling to participate at all, based on the provenance of the survey.

5.3 Results

The outcomes of both the survey and interviews will be synthesised in this section. Direct quotes by interviewees will be examined in the discussion, however, a summary of their thoughts relevant to the survey results are outlined here.

Of the survey respondents, 92% ran farms that had been passed down through their family, with 7% of the respondents farming as tenants, additionally 88% of the respondents owned their farms. No impact on the ownership of the farm was identified. The survey respondents and interviewees were asked their age in decades (20s, 30s etc.), the majority of the survey respondents were in their 40s (33%) or 50s (26%), whereas there was one interviewee in their 30s, 40s, 50s, and 60s. Most of the survey respondents were male (81%), 15% were female and one respondent did not want to provide their gender. One of the interviewees was female the other three were male.

The majority of the survey respondents were olive farmers (82%) (Figure 5.2), whereas all of the interviewed farmers were in orange production. The other tree crops that were reported were: persimmon (*Diospyros kaki*), pomegranate (*Punica granatum*), pear (*Pyrus* L.) and apple (*Malus domestica*). Vine crops such as grapes and kiwis were not included in this analysis.

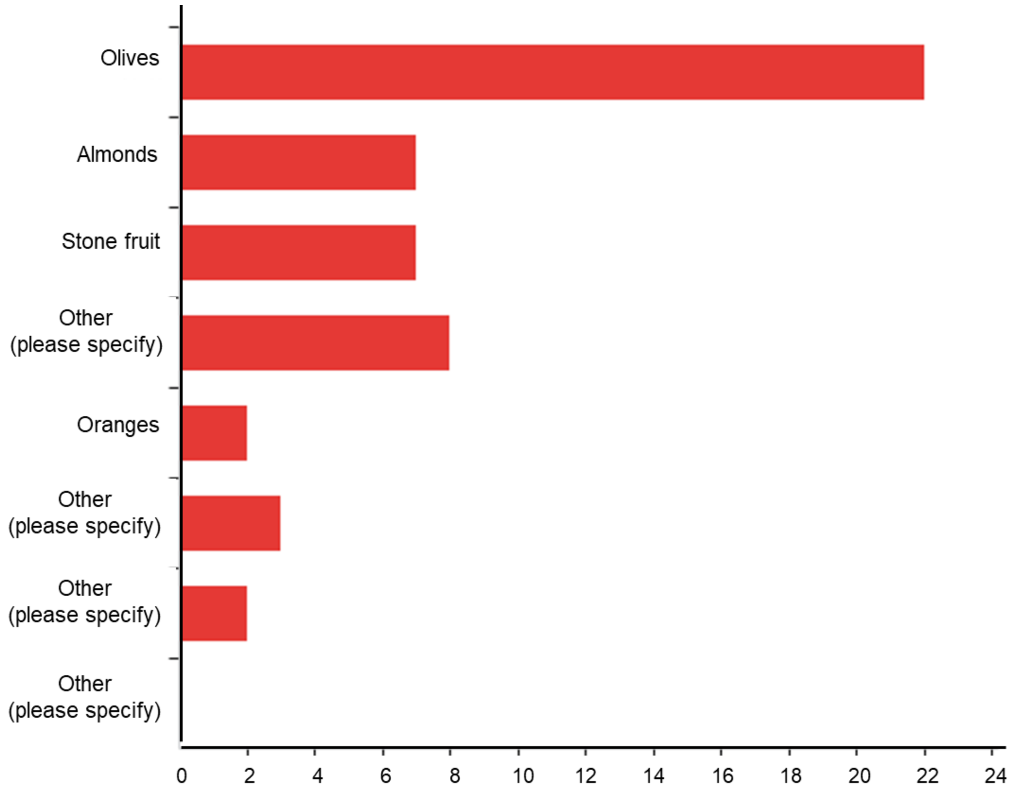


Figure 5.2: Responses to Question 7 *¿Qué cultivos leñosos cultiva? Indique cuántas hectáreas tiene de cada tipo de cultivos leñosos y si es de regadío.* [What tree crops do you grow? Please indicate how many hectares you have of each type of tree crop and whether it is irrigated.]

The majority of the survey respondents used plant cover to control soil erosion (96%), tillage was the least used method to control erosion at 11% (Figure 5.3). The other soil erosion control techniques respondents listed were: “organic matter input with sheep”, “small dams to hold back gullies, “clearing with sheep”, and “leaving grass”. Additional “other” techniques were: “windbreaker with pine trees”; “contour lines”; “rainwater drains for rainwater conveyance”; “contour ploughing”; “mulching with geotextile on some plots”. All of the interviewees used plant cover and mulching from plant cover to manage soil erosion.

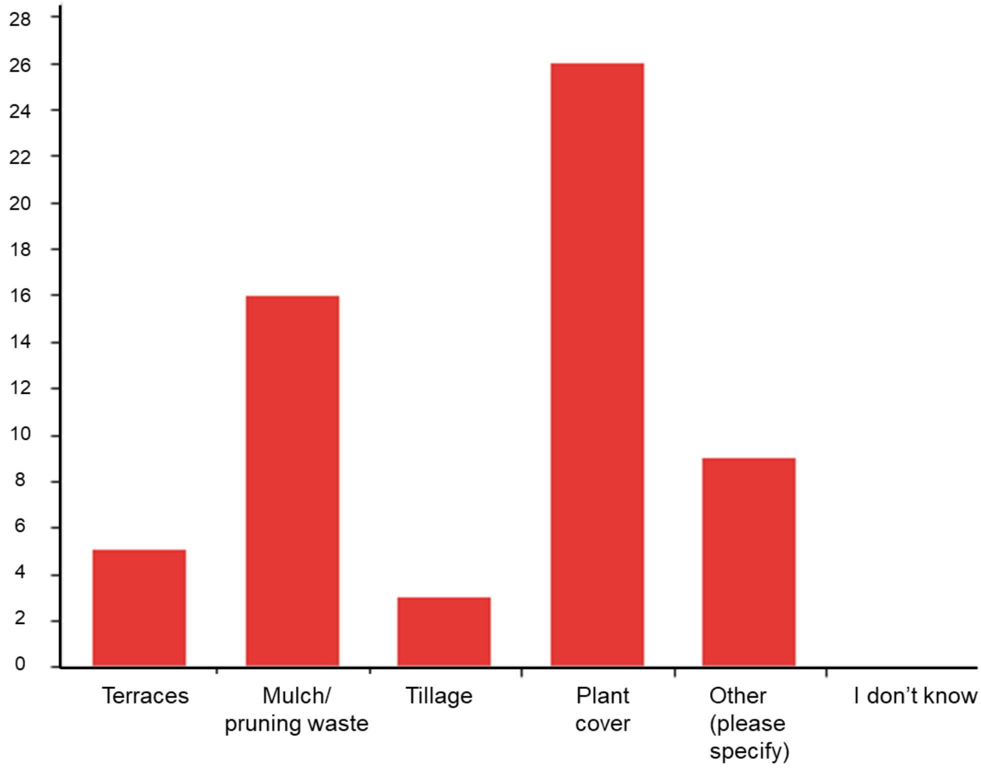


Figure 5.3: Respondents were asked which soil erosion reduction techniques they use. Question 16: *¿Cómo controla la erosión del suelo? Marque todas las que correspondan.* [How do you control soil erosion? Tick all that apply.]

The most common response when asked how the erosion control methods were chosen was that an agronomist recommended them (37%), followed by recommended by fellow farmers (33%) (Figure 5.4). The other reasons (30%) survey respondents use their current erosion control were: “recommended by me as I see it as the best system to control erosion and retain water and nutrients”; “logic and knowledge of organic farming led me to this”. Additional responses were: “personal experience”; “study regenerative agriculture and livestock farming”; “dusting the olives”; “I am an agronomist”. Further responses were: “after a lot of reading and observing the field and contracting knowledgeable people”; “I am convinced of the advantages due to my technical knowledge of the subject matter”. The interviewees either did their own research which led to them using cover crops, or it was recommended by an agronomist.

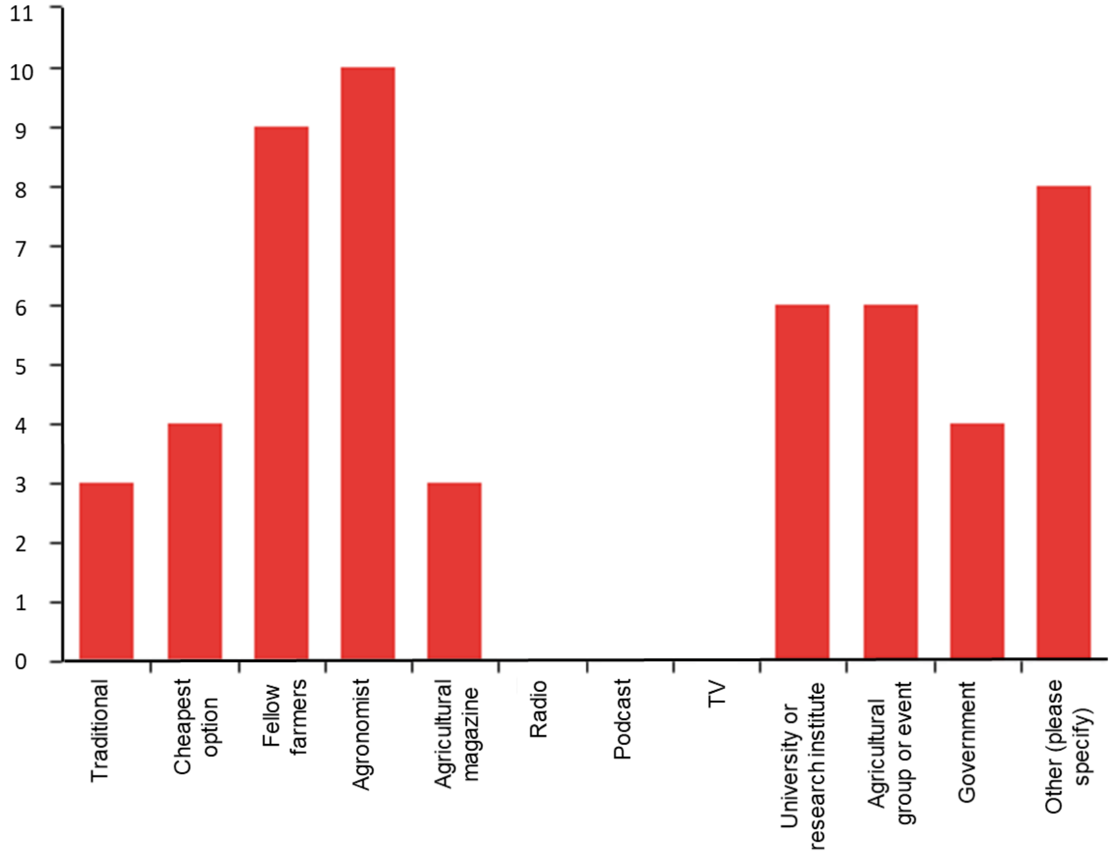


Figure 5.4: The reason that these methods are used was asked in question 19: *¿Cuáles son las razones por las que utiliza sus métodos actuales de control de la erosión? Marque todas las que correspondan*. [What are the reasons you use your current erosion control methods? Please tick all that apply.]

Knowledge is the key limiting factor identified by survey respondents as a barrier to implementing soil erosion control methods (Figure 5.5). Lack of knowledge about which methods are the most effective (47%) and the cost of starting a new method (25%) were the main barriers. The other barriers suggested by the respondents were: "mentality" and "use of herbicides". Interviewees do not think that starting to use cover crops would result in an increase in cost, but it depends on whether herbicides were previously used on the farm and whether spontaneous vegetation was suitable. Two interviewees believed that increased financial support would encourage more people to use cover crops. However, the mentality, or mind set, of farmers was considered a barrier by two other interviewees due to the cultural perception of cover crops being bad management (Keesstra et al., 2019). Nevertheless, increasing evidence of the benefits of vegetation and herbicide restrictions are increasing cover crop use.

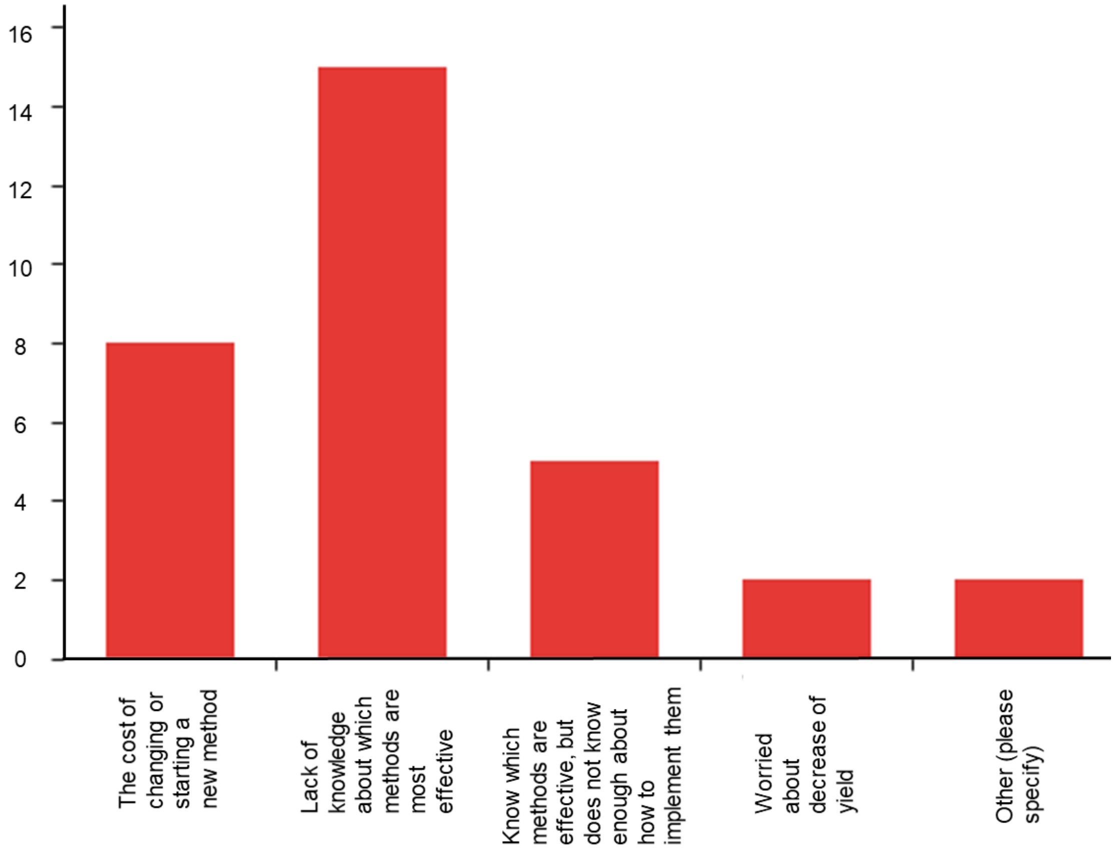


Figure 5.5: Question 25: *¿Cuáles son las barreras para implementar métodos de control de la erosión? Marque todas las que correspondan.* [What are the barriers to implementing erosion control methods? Please tick all that apply.]

5.4 Discussion

Most of the respondents to the survey were olive farmers (82%) (Figure 5.2), while all of the interviewees were orange farmers, nonetheless, 96% of the respondents and interviewees used cover crops to manage soil erosion. This causes a nonresponse bias, as farmers who are not interested in vegetation cover are unlikely to take the time to fill out a survey about it (Phillips et al., 2016). Therefore, the responses from the survey are not reflective of the whole farming population (Phillips et al., 2016), nevertheless the survey answers are valuable and provide more insight into the use of cover crops to control soil erosion.

5.4.1 Use of erosion control methods

There is a high use of cover crops to control soil erosion by the survey respondents (96%) (Figure 5.3). However, this extent of vegetation cover is not reported in the literature: in surveys of over 100 olive farmers 6% (Sastre et al., 2017), 50% (Calatrava Leyva et al., 2007) and 63% (Gómez et al., 2021) used cover crops. Fewer studies have been carried out with citrus farmers apart from the work of Cerdà et al. (2018) who observed that only 10% of the 139 citrus farmers they surveyed used cover crops.

The survey and interviews confirm that farmers do use and are passionate about the many benefits provided by cover crops in tree crop orchards. While they may not be representative of the general farming population, the interviewees in particular found vegetation cover important for multiple reasons. The provision of nutrients by cover crops was clear to one interviewee:

> Vegetation cover … gives me nutrients as well. … we know that the nutrients [from vegetation cover] are helping me because we are not exceeding 200 nitrogen fertiliser units … and the harvest is impressive.

Additionally, 74% of the survey respondents for this chapter thought that vegetation cover increased nutrient and water availability. However, not all spontaneous vegetation is suitable as vegetation cover and sometimes it needs to be replaced with planted cover crops. One interviewee observed that spontaneous vegetation is not suitable in areas where “they proliferate a lot… compete with the crop for nutrients or water…[or] grow very tall”. However, benefits of cover crops were less apparent to citrus farmers in Valencia who requested subsidies to cover water and nutrient use if switching to cover crops (Cerdà et al., 2018), implying that they felt there would be competition between the cover crops and tree crops. Additionally, olive farmers in the south-eastern Madrid area were worried about water and nutrient competition (Sastre et al., 2017).

Furthermore, vegetation was recognised to prevent disease “Phytophthora [brown rot] colonises oranges by splashing [fungal spores onto the trees], on bare soil there is splashing, on grass-covered soil there is no splashing”. These benefits of vegetation cover have also been noted in other surveys: pest and disease control was found by Goméz et al. (2021) to be a higher motivation for olive farmers to use cover crops in Estepa than in Cordoba. These benefits were confirmed by another interviewee as cover crops were part of their integrated pest management:

> So, we use biological control to kill the [mites], so we don't always have to spray with pesticides, we give shelter to the [phytoseiids] during the whole winter, because those [phytoseiids] can feed on the [mites] and on the pollen of the flowers that we have in the vegetation cover.

On the other hand, the citrus farmers interviewed by Cerdà et al. (2018) thought cover crops would increase pests. However, in the survey by Cerdà et al. (2018) spontaneous vegetation was framed as "weeds", which were poorly received by the farmers, with 94% disliking weeds, and only 3% using weeds to control erosion. However, one of the interviewees recognised the value of cover crops to control weeds which are glyphosate resistant:

> There are plants that are resistant to glyphosate… Moreover, the glyphosate eliminates their competition, so they abound. When you mow, with a little bit of time, two years, three years, they disappear because of competition because the grasses push them out.

5.4.2 Information on erosion control methods

Clearing the vegetation between trees has only been common practice since the 1970s using tillage, with herbicide becoming the most common method in the 1990s (Vanwalleghem et al., 2011). This is now seen as the "traditional" practice and there is resistance to the use of cover crops as they are untidy and unclean (Cerdà and Rodrigo-Comino, 2021; Keesstra et al., 2019). One of the interviewees said that when he started to use cover crops in "traditional Valencia" in 1982 he was considered "the dirtiest person in the world". This is challenging for the adoption of vegetation cover as farmers influence each other's uptake of new techniques, with 33% of survey respondents using their erosion control methods based on the recommendation of fellow farmers (Figure 5.4). Agronomists were the main source of information on farming practices for 37% of respondents, only a little more than fellow farmers. Additionally, 26% of the survey respondents stated that they chose their erosion control methods based on their own technical knowledge, observations and research (Figure 5.4). Given the expectation that the group who answered the survey would have more interest in cover crops than the wider farming community, it was unsurprising that a low 11% said that tradition influenced their erosion control decisions (Figure 5.4). This is much lower than findings by Sastre et al. (2016) who observed that tradition was the primary reason that farmers chose their management practices, identified by 50% of their 119 respondents. Although 26% of the respondents use their own technical knowledge and research to choose erosion control methods, these were different respondents to the 22% of whom were guided by a university or research institute (Figure 5.4). Similarly, the interviewees worked with agronomists or were agronomists themselves, in addition to conducting their own research in a non-academic setting, rather than working with universities or research institutes. This indicates that even among the farmers most invested in cover crops there is a lack of awareness of the academic research into erosion control in orchards, which has been happening since the 1960s (Gómez et al., 2021).

5.4.3 Barriers to erosion control

The need to control soil erosion is well-understood in academic circles, with benefits to ongoing agriculture, decreased water pollution, and increased carbon storage, in addition to biodiversity outcomes (Ruiz-Colmenero et al., 2013; Segovia et al., 2017). These factors are not well communicated to farmers, one interviewee stated “[i]t is a problem of awareness”. Moreover, the impacts of soil loss on crop yields can be offset by heavy use of fertiliser (Gómez et al., 2014), so farmers are not aware of the extent of the issue. Furthermore, even when farmers are aware of the benefits of using vegetation to control soil erosion, there are other obstacles such as vegetation between tree rows being perceived by neighbours as “dirty” (Keesstra et al., 2019). An interviewee who has been using cover crops for decades faced this backlash:

> They would see a weed and they would go crazy to remove it. In … the traditional Valencia [in the 1980s], they said we [farmers using vegetation cover] were gardeners back then. You could only see the tree, underneath nothing, absolutely nothing.

Moreover, farmers “always wanted to have a clean field, … feeling that those covers are going to compete with the roots, for nutrients” as competition between the cover crops and tree crops for water and nutrients is a worry for farmers (Gómez, 2017; Basche and DeLonge, 2017). However, “if you explain… that the tree only absorbs the first 30 centimetres, you have a [raised] plateau [for the tree], … grass underneath [is] not going to compete with the roots”.

Some farmers see only positive impacts of vegetation cover regarding the cost of farming, saying “it's a lot cheaper to do it this way than using herbicides, that’s for sure”. But for farmers not yet using cover crops, finances are another concern as “the only [financial support] … is the EU CAP, the Common Agricultural Policy ... But it has nothing to do with vegetation cover management or erosion management”. Both the cost of introducing a new method, and the potential loss of income if the cover crops result in a decrease in crop yield are a worry for farmers (Cerdà and Rodrigo-Comino, 2021). Figure 5.5 demonstrates this as 30% of respondents thought that the cost of starting a new method was a barrier to farmers. Some of the respondents started using conservation methods due to the detrimental impact of erosion on finances, incurred no added cost by changing methods, or thought the ecologicial benefits offset any cost. Furthermore, 7% suggested that worries about loss of yield were a barrier. One interviewee observed that knowledge of native vegetation can help:

> to reduce costs, what you have to study is the type of spontaneous vegetation in the crop you are going to grow, … and if it is worth incorporating some [planted cover] because it favours some kind of nutrient release or if it favours soil aeration, or something else.

An estimate from the Murcia Regional Government in 2007 revealed that maintaining cover crops in an orchard varies from €109-669, with the cost increasing with the steepness; when a slope is steeper than 6%, it is cheaper to use pruning residues as ground cover (Calatrava and Franco, 2011). Financial support to cover these costs, “might … be an incentive for them to leave vegetation cover and maybe through this incentive they would realise that it is something beneficial”, resulting in increased farming backing for plant cover.

Successfully using vegetation cover requires taking the time to understand the spontaneous vegetation on the farm and the impacts (both positive and negative) this has on pests, diseases, nutrients, water and access and consequently requires a high level of commitment from farmers (Gómez et al., 2021; Novara et al., 2021). However, knowledge is a barrier, Figure 5. 5 reveals that 47% of the respondents think that lack of knowledge about the most effective methods is a barrier to farmers, while 16% consider that farmers are aware of which methods are best to use but do not know how to implement them. The respondents using erosion control methods have experimented over years or sought out experts (agronomists and fellow farmers) to learn more (Figure 5.4)

5.4.4 Future of erosion control methods

Soil erosion is worsening as climate change progresses, and the use of fertilisers will not be able to mask the impacts of soil loss on crop production for much longer (Gómez et al., 2018; IPCC, 2014). Additionally, the rising cost of fertilisers (Eardley, 2022; Eurostat, 2022) is likely to result in the need to “to create a more sustainable culture. Currently … there is a lot of agriculture that is not sustainable” (quoted from an interview). This, in addition to increased political pressure, may force farmers to re-evaluate their farming methods and move towards more sustainable techniques (Wuepper, 2020). A move that one interviewee thought the farming culture was ready for:

> Well, in the past people have always tried to throw herbicide on everything, but I think that in recent years people have been changing their mentality and are beginning to see the positive side of vegetation cover.

The use of cover crops or ground cover to control erosion are already legally required in Spanish orchards with a slope of more than 10% (Taguas and Gómez, 2015). Glyphosate, currently widely used by farmers to control spontaneous vegetation (Keesstra et al., 2019), will lose its approval as a plant protection product in the European Union in December 2022 (European

Commission, 2022). This policy change may lead to “people, with all the herbicide restrictions, … [doing] more and more [cover cropping]”, and an increase in mowing to control cover crops.

An interviewee highlighted the importance of this PhD topic:

> I think that we would also need a study of which plants are more interesting for which specific crops, that is, the best for citrus, maybe a mixture of plants that are more suitable than others, right?... Or for these natural enemies, which is the real effect of these plants with biological control, that [research] is still being developed.

The next step is to increase the dissemination of the research findings to farmers and agronomists, as “[a]ppropriate support would be training at the level of consciousness... at the level of the workers, at the level of the farmers.”. Education of stakeholders in the potential benefits or issues with spontaneous vegetation, encouragement of the provision of financial support is necessary (Sastre et al., 2016; Cerdà et al., 2018).

5.5 Conclusions

This chapter demonstrates the passion that some farmers feel for cover crops and the many benefits they bring to orchards. However, the reluctance to use cover crops is limiting the widespread use of cover crops as indicated in the interviews and literature, particularly in orange orchards (Cerdà et al., 2018), or on steep slopes (Calatrava and Franco, 2011). As hypothesised, most farmers responding to the survey did not look into the findings of universities and research institutes (22% did). Furthermore, knowledge limitations were considered by 53% of respondents to be more of a barrier to cover crop use than financial concerns (31%). Therefore, the evidence about cover crop benefits needs to be communicated directly to farmers and agronomists, as this is where most of the survey respondents receive information. This, along with increased financial support, will empower farmers to overcome barriers such as concerns about crop yields and community perception of bad management (Sastre et al., 2016; Cerdà et al., 2018).

6. General Discussion

Soil erosion is a major global issue (IPCC, 2014). Due to the climate, topography and farming practices Mediterranean hillside orchards are particularly vulnerable to soil loss (Raya et al., 2006). The issues facing olive and orange trees are outlined in Figure 6.1. Extensive research has been conducted into the efficacy of plant cover to reduce soil erosion in Mediterranean orchards (e.g. Gómez, 2017). However, the uptake of cover crops for soil conservation by farmers is relatively low, though difficult to quantify with 6% to 63% of olive farmers using cover crops (Sastre et al., 2016; Gómez et al., 2021). Farmers are more likely to use seasonal cover crops to reduce water competition during the summer (Figure 6.1). Plant trait analysis is helpful to quantify plant features which could prevent or exacerbate soil erosion (Figure 6.1). However, plant trait analysis has not been thoroughly carried out on seasonal cover crops (Repullo-Ruibérriz de Torres et al., 2018). This was the key research gap addressed by this thesis, other knowledge gaps are outlined in Figure 6.1 and Table 6.1. Additionally, there is a lack of information available for farmers to determine whether a plant cover is appropriate for erosion control. This is exacerbated by a communication barrier between farmers and researchers (Taguas and Gómez, 2015). Furthermore, there is uncertainty about the impact of cover crops on water and nutrient availability for the tree crops (Keesstra et al., 2016; Sastre et al., 2020; Raya et al., 2006).

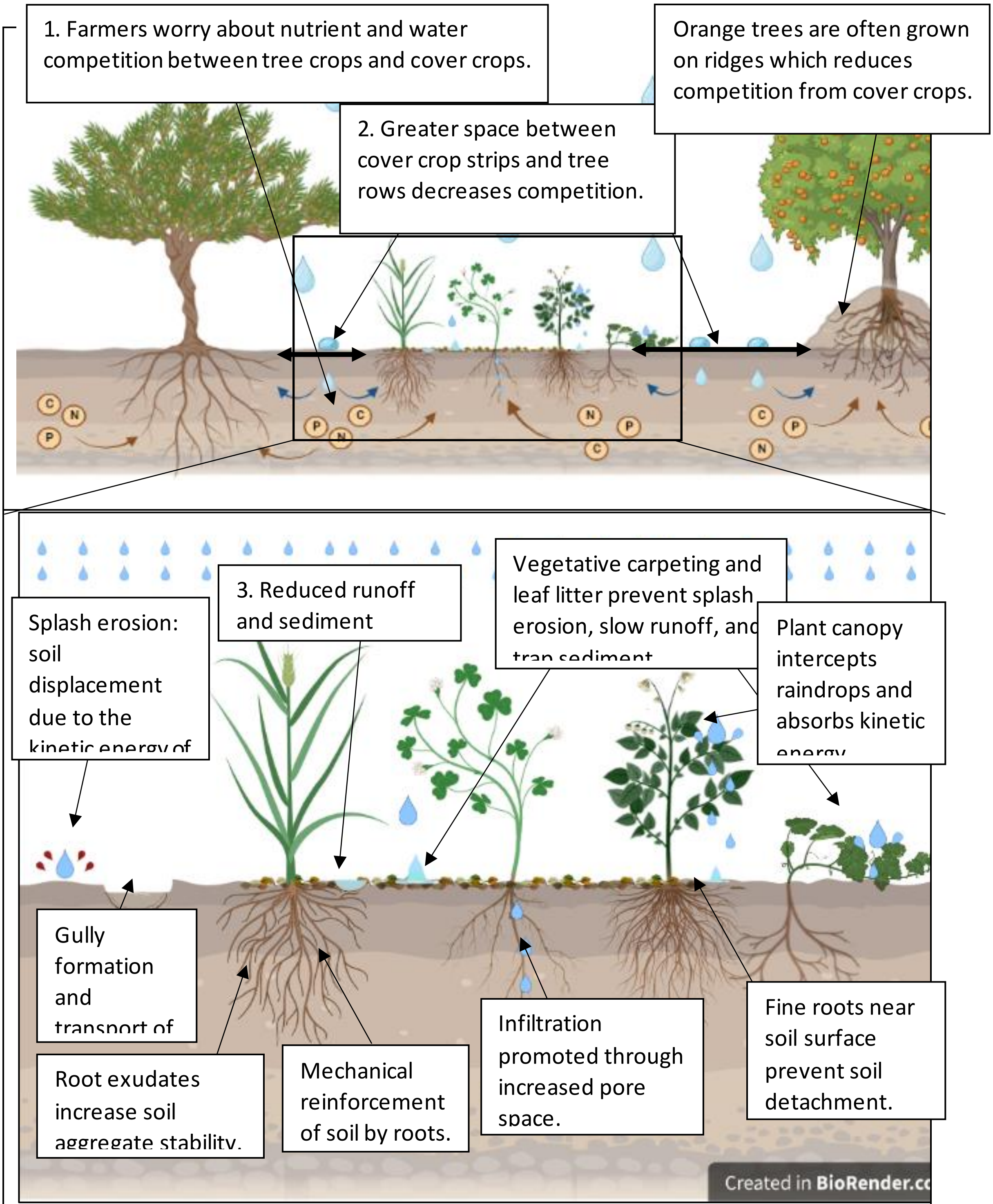


Figure 6.1: An annotated diagram of the impacts of cover crops on tree crops, and above and below ground plant traits on soil erosion and runoff.

Table 6.1: Key knowledge gaps in the area of plant traits and erosion control in Mediterranean orchards.

	Annotation from Figure 1.4	Knowledge gap associated with this factor.
1	Farmers worry about nutrient and water competition between tree crops and cover crops.	Fast growing, annual species have been increasingly used as cover crops in orchards to reduce water competition during the summer. However, the erosion reducing plant traits of these species are under-studied (Figure 1.6). Farmers are not kept informed of all the cover crop research that is carried out, and are slow to take up techniques which are shown to be beneficial.
2	Greater space between cover crop strips and tree rows decreases competition.	There is conflicting evidence about whether cover crops do compete with tree crops. It is not known whether cover crops can increase water and nutrient availability to tree crops. This could happen through reduced evaporation compared to bare soil, promotion of infiltration and increase of C and N in the soil due to plant matter.
3	Reduced runoff and sediment movement.	The efficacy of certain traits to reduce splash erosion is not fully understood. Furthermore, the plant traits of species which are suitable for seasonal use in Mediterranean orchards have not been examined.

The aim of this research was to investigate the plant functional traits of fast growing annual species and expand the existing knowledge of the effectiveness of these species to control erosion and their suitability for use with tree crops. This aim was addressed in the experiments detailed in Chapters 2 to 5. Chapter 2 investigated the above ground traits (above ground biomass, height, specific leaf area, tillers, modulus of elasticity), below ground traits (actual root length, specific root length, average root diameter, root dry matter and root volume), evapotranspiration and infiltration. Chapter 2 concentrated on the first research question (Table 6.2) to conduct plant trait analysis on fast growing annual species native to southern Spain to determine which have the most potential to reduce soil erosion. Based on the outcomes four species with good potential to reduce erosion, and complementary traits, were taken forward to Chapter 3. Chapter 3 focused on the second research question (Table 6.2), to determine how the most effective species from Chapter 2 responded to competition from weeds in a field trial, and whether soil chemistry suggests they would be competition for tree crops. Therefore, Chapter 3 was a field trial of false broom (*B. distachyon)*, red broom (*B. rubens)*, alfalfa (*M. sativa)* and bladder campion (*S. vulgaris)*, assessing the nutrient impacts of the species on the soil. This chapter was impacted by COVID-19, the field trial had initially been set up to conduct runoff analysis and determine the impact of select plant traits in soil loss. Chapter 4, concentrated on the third research question (Table 6.2), and made up for the loss of runoff simulation in Chapter 3. Chapter 4 used rainfall simulation to determine the impact of monocultures (false broom, *B. dista,* alfalfa*, M. sativa,* and bladder campion *S. vulgaris*) and mixes on soil loss and runoff. Finally, the fourth research question (Table 6.2), about how farmers respond to soil erosion and potential communication barriers , was addressed in Chapter 5 where farmer experiences and opinions were sought though a survey and interviews.

Table 6.2 Research questions for this thesis

	Research questions	Outcomes of these questions
1	Which commonly used seasonal cover crops have beneficial plant	False broom *(B. distachyon)*, red broom (*B. rubens)*, alfalfa (*M. sativa)* and bladder campion (*S. vulgaris)* all performed well for

	traits to prevent soil erosion?	above and below ground plant traits and were expected to work well in a mix.
2	Do some of the cover crop species deplete soil nutrients more than others? Are some species more vulnerable to competition from weeds?	There was no difference in nutrient status of the soil under the different treatment. This shows that none of the treatments depletes soil nutrients more than others, for the length of the field trial. The only planted species with significantly greater biomass than the other species was alfalfa (*M. sativa*). However, this species was also the most prevalent weed in the field site which was not known when the field site was selected.
3	Which traits are associated with reduced soil loss and runoff?	Above ground plant traits (above ground biomass and soil cover) had a greater impact on reducing soil loss than below ground plant traits (below ground biomass and average root diameter). The dominant identity of the species affected soil loss prevention.
4	How do farmers deal with soil erosion and is there a communication barrier between farmers and researchers in Spain?	The farmers surveyed were passionate about the use of cover crops for multiple reasons, including soil conservation. They suggested that lack of knowledge was a barrier to other farmers which does indicate a lack of communication.

6.1 Plant traits to control soil erosion

In the context of orchard farming in Spain, farmers are worried about competition between cover crops and tree crops (Taguas and Gómez, 2015). Therefore fast growing species that could be used as seasonal overwinter (October to April) cover crops were selected for this project. The species that were used in this thesis are listed in Table 6.3, along with results from published studies that used the same species, and whether the outcomes of this thesis confirm or refute these findings.

Table 6.3: The species analysed in this thesis, and other studies that have examined the impacts of these species on soil loss and other plants.

Species	Chapter used in			Studies the species were used in	Outcomes of the studies	Contribution of this thesis to existing knowledge
	2	3	4			
False broom *(B. distachyon)*				Sastre et al. (2020)	A permanent *B. distachyon* treatment was used which increased soil organic carbon (2.15 Mg ha^{-1} compared to tillage). However, due to nitrogen competition *B. dista* caused a significant decrease in olive yield, 32.4% of that in tillage treatments.	Chapter 2 reported no change in soil carbon and nitrogen under false broom (*B. dista*). This does not tally with the findings of Sastre et al. (2020) and García-Díaz et al. (2017). However, both of these studies established the treatments for two to three years. This allows for much longer time for the vegetation to condition the soil, compared to the six months that was possible in Chapter 4. The ground cover achieved by false broom (*B. dista*) in
				García-Díaz et al. (2017)	*B. dista* had significantly more (82%) vegetation cover than tillage in this study, but no significant difference in runoff. However, it also had significantly lower nitrate (34%	

					lower) and ammonium (51% lower) than the tillage treatment (0.76 and 0.79 respective.	Chapter 4 was 86% higher than bare soil. This is comparable to that reported by García-Díaz et al. (2017) and Repullo-Ruibérriz de Torres et al. (2018). Soil loss was reduced by 84% by *B. dista*, compared to bare soil. This is similar to that reported by Repullo-Ruibérriz de Torres et al. (2018). However, there was no significant difference in runoff between *B. dista* and bare soil in Chapter 4.
				Repullo-Ruibérriz de Torres et al. (2018)	*B. dista* significantly decreased runoff (81.2%), soil (by 93.2%) and soil carbon loss (by 94.9%) compared to tillage. Additionally, *B. dista* had significantly greater ground coverage (94.3%) than tillage.	
Borage (B. officinalis)				Gómez et al. (2018)	Borage was used as part of a seeded mixed cover crop. This treatment had significantly lower soil loss, 83% lower than conventional tillage. There was no significant difference in the	This treatment was not used in Chapter 4 where soil loss and runoff was measured. Based on the plant trait analysis in Chapter 2, this species might provide below ground benefits

					runoff between the tilled and seeded treatments.	to the mix. However, borage had a large degree of variation within the replicates (Figure 2.4).
Red broom *(B. rubens)*				Repullo-Ruibérriz de Torres et al. (2018)	*Bromus* was one of the species that made up a spontaneous vegetation treatment. The spontaneous treatment had significantly lower runoff (63.3%), soil carbon (95.7%) and soil loss (93.7%) than the tilled treatments.	Red broom was also not used in Chapter 4 where soil loss and runoff were examined. The findings of De Baets et al. (2007a)are supported by the plant trait analysis in Chapter 2. Red broom had the greatest specific root length of the species analysed which fits with the root length density and root density reported by De Baets et al. (2007a).
				De Baets et al. (2007a)	*B. rubens* was reported, anecdotally, to one of the worst species in reducing concentrated flow erosion in abandoned fields. This species had fine roots of less than <1 mm. *B. rubens* also had large	

					root length density (0.71) but small root density (0.13 kg m^{-3}).	
Field marigold *(C. arvensis)*				Gómez et al. (2018)	Field marigold was used as part of a seeded mixed cover crop. This treatment had significantly lower soil loss, 83% lower than conventional tillage. There was no significant difference in the runoff between the tilled and seeded treatments.	Field marigold had a high degree of variability in Chapter 2. This supports the lack of significance in the difference of runoff between the mix with C. arvensis and bare treatments reported by Gómez et al. (2018).However, the reduction of runoff identified by Repullo-Ruibérriz de Torres et al. (2018) and Zuazo et al. (2009) does not correlate with *C. arvensis* plant traits identified in Chapter 2. This may be due to the traits of the other species in the mix that field marigold was part of.
				Repullo-Ruibérriz de Torres et al. (2018)	*Calendula* was one of the species that made up a spontaneous vegetation treatment. The spontaneous treatment had significantly lower runoff (63.3%), soil carbon (95.7%) and soil loss (93.7%) than the tilled treatments.	

				Zuazo et al. (2009)	*C. arvensis* was identified as one of twelve species in a native vegetation treatment. The native vegetation treatment had significantly lower soil erosion (59%) and runoff (94%) than the tillage treatment. There was no significant difference between the native vegetation barley strips on soil loss and runoff.	Field marigold may have contributed to the reduction in soil loss identified by Gómez et al. (2018), Repullo-Ruibérriz de Torres et al. (2018)and Zuazo et al. (2009). This is particularly due to the high root volume and average root diameter, both with low variability (Figure 2.4).
White rocket *(D. erucoides)*				Cerdà et al. (2018)	*Diplotaxis erucoides* was one of the spontaneous vegetation species on the site which were used as treatment. There was no significant difference between the spontaneous vegetation and the cover crop of vetch and oats for any of the	Apart from larger stem elasticity then the other species examined in Chapter 2, white rocket was not outstanding in any of the erosion control plant traits measured in this thesis. Furthermore, this species had the greatest water usage and would not be expected to

					parameters measured in this study.	contribute much to eoriosn control. This supports the findings of Cerdà et al. (2018).
Annual ryegrass *(L. rigidum)*				Rodrigues et al. (2015)	Annual ryegrass was one of the spontaneous species in this study area. There were two treatments with natural vegetation for this study, one with added fertiliser, one that was not fertilised. The natural vegetation treatments had significantly lower plant N than the legume treatment. The olive trees of the legume plots had significantly higher leaf N than the natural vegetation without fertiliser. There was no significant difference in olive leaf N between the legume and	Annual ryegrass was not used in the field site (Chapter 3) for this thesis. Therefore, the impact of annual ryegrass on N in soil and plants cannot be compared with those reported by Rodrigues et al. (2015).The reduction in sediment yields observed by Gómez et al. (2009a) correlates with the large above ground biomass, average root length and root volume identified in Chapter 2 (Figure 2.4).

					natural vegetation without fertiliser.	
				Gómez et al. (2009a)	Cover crops (*Lolium rigidum* or *multiflorium*) significantly reduced runoff (by 64%) and sediment yields (by 98%) compared to conventional tillage.	
Burr medic *(M. polymorpha)*				Ovalle et al. (2006)	This study quantified biological nitrogen fixation of different annual legumes. Burr medic had significantly lower dry matter than yellow serradela (*Ornithopus compressus*), balansa clover (*Trifolium michelianun*), and subterranean clover cv. Clare (*Trifolium subterraneum* cv. Clare). There was no significant difference between burr medic and the	Burr medic was not used in the field site (Chapter 3) where soil and plant N was analysed. Therefore, limited comparisons can be made with the studies by Ovalle et al. (2006) and (2010) . However, the low dry matter reported by Ovalle et al. (2010) is opposed by the high above ground biomass observed for burr medic in Chapter 2. On the other hand,

					other species with regard to N concentration. However, this species had significantly lower N accumulation than yellow serradella, balansa clover and subterranean clover cv. Clare. But burr medic had significantly greater N accumulation than (*Ornithopus sativus*) and subterranean clover cv. Gosse. Burr medic had significantly less plant N derived from air than yellow serradella and balansa clover.	Ovalle et al. (2006) and (2010) were investigating the transfer of N to vines so the species used may not be suitable as erosion controlling seasonal plant cover
				Ovalle et al., (2010)	Burr medic was one of the species in a legume mix of early maturing cultivar. This mix had significantly lower dry matter and N than a mix of late maturing cultivars. The mix with	

					burr medic had significantly lower contribution of N to vine crops than the other mix.	
Alfalfa *(M. sativa)*				Raese et al. (2007).	Alfalfa was present in the plots with low N fertiliser additions.	Alfalfa had fast infiltration compared with bare soil in the experiment by Li and Pan (2018).This is supported by the fast infiltration observed in M. sativa plots in Chapter 2. The decreased rate of runoff reported by Li and Pan (2018) was not corroborated by Chapter 4 where there was no significant difference with bare soil at any time point. Additionally, the large decrease in soil loss identified by Li and Pan (2018), was on ly observed in the first subsamples in Chapter 4 (figure 4.3).
				Li and Pan (2018)	*M. sativa* was one of three vegetation treatments assessed with a control under simulated rainfall. Infiltration of alfalfa was 59% faster than bare soil. Runoff from alfalfa plots was 37% of that from bare plots. Alfalfa decreased soil loss by 84.6% compared to bare plots.	

Barrel medic *(M. truncatula)*				Soriano et al. (2016)	Barrel medic had significantly, 37.7%, smaller fine root biomass than red broom. Ground cover of barrel medic was 42% lower than of red broom.	In Chapter 2, barrel medic had larger (although not significantly) average root diameter than red broom (*B. rubens*). This supports this findings or Soriano et al. (2016). While ground cover of barrel medic (*M. truncatula*) was not measured in this thesis, there was no significant difference between the above ground biomass of (*M. truncatula*) and red broom (*B. rubens*).
Bladder campion *(S. vulgaris)*				Gómez et al. (2018)	Bladder campion was used as part of a seeded mixed cover crop. This treatment had significantly lower soil loss at 17% of conventional tillage. There was no significant	Differing from the findings reported by Gómez et al. (2018), in Chapter 4, runoff from Bladder campion plots had consistently lower runoff than bare plots, significantly lower at

					difference in the runoff between the tilled and seeded (19% higher than from tilled) treatments.	the final subsample. However, the soil loss reported by Gómez et al. (2018) are supported by the results in Chapter 4 where the bladder campion plots had significantly lower soil loss than bare soil (except for the last subsample).

Although the species were selected for quick establishment, there were a range of heights, specific leaf areas, root diameters and root lengths among the species, understanding these traits is important for identifying species for erosion control (Bardgett et al., 2014; Freschet et al., 2017). Above (above ground biomass, specific leaf area, modulus of elasticity, tillers, and plant height) and below ground traits (root volume, actual root length, specific root length, and root dry matter) were examined. This was initially to compare the ten species and select the ones that had the greatest potential to reduce erosion at a sub-process level (Chapter 2), then to examine how the species with these traits correlated with soil loss (Chapter 4). All of the papers listed in Table 6.2 examined these species, although none of them examined the influence of their plant traits on soil erosion. This was new knowledge generated by this thesis.

The performance of each species relative to the others for particular traits varied between chapters. For instance, in Chapter 2 *B. dista* had the highest above ground biomass (AGB) (of the species taken into Chapter 3) with an average of 4.0 g per species. But in Chapter 3 *B. dista* had the lowest AGB with a mean of 0.7 g in each treatment it was present. In Chapter 4 *B. dista* had the greatest AGB of all the treatments with a mean of 301.0 g in the single species plots. AGB is not a parameter widely reported in conjunction with soil erosion. Cover is more frequently measured, particularly as the publications to date that examine plant traits and soil loss prevention focus on perennial species (De Baets et al., 2007a; Quinton et al., 1997) so destructive sampling is unsuitable. Although not examining soil erosion, Baxendale et al. (2014) recorded AGB and reported that monocultures had a greater total biomass when grown in soil conditioned by a fast growing species, whereas treatments with a mix of species grew better when following slow growing plants. However, this does not explain why *B. dista* experienced lower biomass in Chapter 3 when grown in a field site which had previously contained fast growing weeds. The soil chemistry of the field site (Chapter 3) reveals more organic matter, Olsen P, ammonium and nitrate than that of the soil used in Chapter 4. However, in the field watering occurred rarely and the plants were predominantly rainfed, whereas in the polytunnel the plants were watered nearly daily. This may explain why false broom (*B. dista*) did not grow as well in the field, although B. dista is well adapted to the Mediterranean climate (Des Maris et al., 2017). Additionally, in Chapter 2 *M. sativa* had the second fastest infiltration (mean of 165.3 mm h^{-1}), but in Chapter 4, the *M. sativa* monoculture had the highest runoff of the vegetated treatments (978 ml min^{-1}), indicating slow infiltration (Palese et al., 2014). The bulk density was not recorded for either of these chapters, however, the infiltration cylinders and runoff boxes were filled with similar methods. The only difference being that the soil in the runoff boxes was allowed to settle and then filled to the rim of the box. Due to this there may have been higher bulk density in the runoff boxes which affected runoff. Although lower than the infiltration recorded in Chapter 2, Cerda et al., (2021) recorded infiltration as 80.05 – 142.4 mm h^{-1}, under a leguminous cover crop, of which *M. sativa* was one of two species, faster than the control treatment. Li and Pan (2018) stated that *M. sativa* had the highest infiltration (18 mm hr^{-1}) and lowest runoff (42 mm hr^{-1}) of the cover crops used, and reported that above ground biomass and roots were the most important factors for reducing runoff under rainfall. Li and Pan (2018) found that roots were the most important part of *M. sativa* to reduce sediment yield under rainfall alone, and rainfall with overland flow. This is not reflected in Chapter 4, where there was no significant relationship between soil loss and below ground biomass, however *M. sativa* had lower (though not significantly) below ground biomass than *B. dista* and *S. vulgaris* (Figure 4.5a). Furthermore, in Chapter 2 *M. sativa* had significantly smaller average root length (ARL) than *B. dista* and *S. vulgaris;* the legume also had significantly smaller root volume than *B. dista*. Unfortunately, below ground biomass could not be measured for Chapter 3 due to COVID-19 as the collaborators in Spain were limited to the time they could spent in the field and what they could collect. It would be interesting to know how the below ground traits of *M. sativa* compared to the other treatments in the field.

6.2 In-field impacts of cover crops

In Chapter 3, the C:N ratio and N content of the plants (particularly *M. sativa*) indicated potential enrichment of the soil if the plants were left on the field as mulch, as described in section 3.4.2. Farmers in Chapter 5, who have decreased fertiliser use since implementing cover crops, confirmed this.

However, this is missing from the literature. Although 75% of the olive farmers surveyed by Gómez et al. (2021) were motivated to use cover crops due to the improvement of soil fertility, the use of cover crops to reduce fertiliser use for tree crops is not present in the literature. None of the other surveys referenced in Chapter 5 (Calatrava Leyva et al., 2007; Sastre et al., 2017; Cerdà et al., 2018) mentioned an increase in soil fertility. However, in Chapter 5, the farmers interviewed specified that where they use fertiliser it is only applied to the base of the tree crops, which may account for the low nitrate and ammonium values observed in Chapter 3.

The average N in false broom (*B. dista*) leaves recorded by Sastre et al. (2020) was 1.5 %, which was lower, but not significantly, than in the spontaneous vegetation and tillage treatments, however, the *B. dista* leaves contained significantly lower N than the bitter vetch (*Vicia ervila*) treatment. This is much higher than the nitrate and ammonium percentages recorded in Chapter 3. However, false broom (*B. dista*) was observed to decrease ammonium content in the soil compared to other treatments by García-Díaz (2017), but none of the treatments in Chapter 3 depleted soil nutrients. However, Table 6.3 indicates that the vegetation cover of false broom (*B. dista*) was lower in Chapter 3 than Chapter 4, which may signify that there was less opportunity for the ammonium use in the field reported by García-Díaz et al. (2017). Furthermore, Sastre et al. (2020) reported that false broom (*B. dista*) had the biggest impact on soil parameters of all the treatments, with an increase in soil organic carbon of 1.0 Mg ha^{-1} yr^{-1}, however, this is contradicted by the findings in Chapter 3 as there was no increase in organic matter under false broom (*B. dista*). However, the time frame over which Chapter 3 was conducted was shorter than the three years that the experiment by Sastre et al. (2020) took place over.

Table 6.3: The mean vegetation cover for the treatments used in both Chapter 3 and 4. The treatments marked with an asterisk were significantly different ($p < 0.05$ with an unpaired t-test).

	Vegetation cover (%)	
Treatment	Chapter 3	Chapter 4

*B. dista**	41.4*	85.8*
*M. sativa**	74.2*	40.6*
S. vulgaris	68.4	76.2
Mix of *B. dista, M. sativa, S. vulgaris*	67	59.9

Vegetation cover varied significantly ($p < 0.05$), for *B. dista* and *M. staiva* between Chapter 3 and Chapter 4 (Table 6.3), cover was not recorded for Chapter 2 as there was only a single plant per pot. This variation is reflected in the literature: Repullo-Ruibérriz de Torres et al. (2018) observed that *B. dista* had significantly lower ground cover than the other treatments (70.3% averaged over two years). This correlates with the observation in Chapter 3. Whereas García-Díaz et al. (2017) reported that *B. dista* had higher, although not significantly, ground cover than spontaneous vegetation , similar to Chapter 4 (Table 6.3). Despite this higher *B. dista* cover, that treatment was noted to have less of an impact on runoff reduction than spontaneous vegetation in the study by García-Díaz et al (2017). However, this observation was contradicted in Figure 4.4d as increased vegetation cover was shown to significantly reduce runoff, irrespective of treatment.

Although *M. sativa* had a low vegetation cover (significantly lower than the other treatments) (Figure 4.4b and d, Table 6.3) it was the dominant species in the mix in Chapter 4. This resulted in increased soil loss from the mixed treatments, as this species was the least effective at controlling erosion. Extrapolating from Chapter 4 and the widely accepted understanding that legumes are not effective at controlling erosion (e.g. Raya et al., 2006; Sastre et al., 2016) the farm used for the Chapter 3 field site would benefit from planting cover crops to complement the spontaneous *M. sativa* growth to reduce erosion. Even though *M. sativa* had higher vegetation cover in Chapter 3 than Chapter 4 (Table 6.3) this was due to the influence of weeds, rather than a better performance of the planted species. On the other hand, the field site used in Chapter 3 is likely to get a high degree of nutrient transfer from the weeds to the soil if they are left on the soil surface after killing. Craswell et al. (1997) reported that legume shrubs were less effective at controlling soil loss and runoff than other plant functional types. However through nutrient transfer to the crops they were important for maintaining the economic sustainability of the farming system.

6.3 Farmers' attitudes to cover crops

The use of fast establishing plants as cover crops in Spain has been carried out in experiments since the late 1990s (Gómez, 2005). However, the extent to which cover crops are used is difficult to estimate and varies in Spain according to regions and crops. For instance in surveys of over 100 farmers 10% of citrus farmers (Cerdà et al., 2018) and 6% (Sastre et al., 2017), 50% (Calatrava Leyva et al., 2007) and 63% (Gómez et al., 2021) of olive farmers used plant cover with tree crops. There are multiple barriers to the use of cover crops, such as finances, including lack of awareness of the economic value of soil (Calatrava Leyva et al., 2007) and loss of crop yield due to competition (Keesstra et al., 2019). Nevertheless, Chapter 5 reveals that users of cover crops think a lack of knowledge of sustainable management options for other farmers is a key issue.This is confirmed by Cerdà et al. (2018) who report that the loss of agrarian extension departments has affected knowledge transfer to Spanish farmers. The necessary knowledge exists in academic circles but there is a lack of communication between the researchers and farmers (Chapter 5) (Cerdà and Rodrigo-Comino, 2021). As reported in Chapter 2, native species that grow naturally in Spain throughout olive and orange growing regions are variable in their potential erosion controlling abilities. Therefore, education for farmers and agronomists to recognise species with useful traits is necessary. Furthermore, farmers should be informed about the potential for cover crops to provide nutrient enrichment to the soil and offset fertiliser costs (Chapters 3 and 5), and educated about the impact of vegetation to control soil loss (Chapter 4). Providing this information to agronomists and educating farmers in groups would be the most effective way of achieving this (Chapter 5) (Calatrava Leyva et al., 2007).

6.4 Implications

Based on the knowledge gaps identified in Figure 6.1 and Table 6.1, the first knowledge gap was partially filled. Extensive examination of plant traits was carried out in Chapter 2, these traits were chosen for their erosion reducing potential. However, in Chapter 4 where erosion and select traits were analysed, not all of the species or traits from Chapter 2 were able to be examined. This was due to time and space restrictions. The farmers surveyed and interviewed in Chapter 5 revealed that they think lack of knowledge is a barrier to other farmers implementing cover crops to control soil loss. This supports the knowledge gap identified within the farming community. While this has not been addressed by this thesis, a report of the findings will be disseminated to farmers who have taken part in data collection. The second knowledge gap was not addressed as evaporation was not measured, infiltration was not carried out on bare soil so this could not be compared with the treatments used in Chapter 2 or Chapter 3. Furthermore, in the field trial in Chapter 3 no samples of bare soil were collected so it was not possible to determine any impact of the treatments on the soil. This thesis has filled the third knowledge gap – understanding the plant traits of species suitable for seasonal cover crop use.

The practical and policy implications of this PhD revolve around the understanding of the role of plant traits to control erosion in short-term cover crops. Additionally, improved communication between researchers and farmers to enable farmers to better understand the risks and benefits of cover crops is required (Cerdà et al., 2018). Funding for group educational events, training for farmers and agronomists, increased understanding of effective knowledge sharing, and increased subsidies to offset any additional costs are needed (Cerdà et al., 2018; Thomas et al., 2020). Thomas et al. (2020) report that in the UK farmers acquire status in their community through experience and effective advisors to farmers also require a standing of trust in the farming community, primarily gained through “demonstrating contextualised knowledge” but also by the length of time spent working with farmers.

This project was in partnership with Primafruit with an aim to provide pertinent research outcomes to them and their farmers. To provide this a report was produced for them giving a brief summary of the research and the resulting recommendations (Appendix 3). Given the findings in Chapter 5 that there is a communication barrier between farmers and researchers, it was advocated that Primafruit provides information to their farmers about how to identify effective traits in their spontaneous vegetation (Chapter 2), in a non-destructive, quick manner. While some spontaneous vegetation needs to be removed due to pest hosting or high water use (Chapter 5) (Keesstra et al., 2016; Novara et al., 2021), providing information on effective traits would allow farmers to make more informed decisions about whether planted cover crops are needed. Furthermore, it was suggested that the industry supports the further education of agronomists into sustainable soil managements. Some farmers find that changing soil management techniques requires a financial input (Taguas and Gómez, 2015) so it was advised that where that happens industry offsets the cost. Finally, it was recommended that Primafruit encourage other food companies to support farmers to make sustainable changes, and to continue funding research.

6.5 Further work

To expand on the work carried out in Chapters 2 and 4, it would be ideal to conduct more mesocosms. This would allow for more traits to be examined and related to soil loss and runoff quantity. Additionally, different ratios of species in the mix would add the knowledge of the dominant identity of legumes, and how this impacts the performance of the mix. Rainfall simulation could be carried out on vegetated plots as done in Chapter 4, but also could be executed after above ground biomass has been removed so that the impact of below ground traits alone could be better understood.

Ideally another attempt at Chapter 3 would be undertaken to use in field runoff analysis to understand how plants (specifically, false broom (*B. distachyon*), alfalfa (*M. sativa*) and bladder campion (*S. vulgaris*)) in a less controlled environment affect erosion. Analysing all of the traits studied in Chapter 2 would be ideal in this field setting, and whether the impact of below ground traits is greater in the field. Building on this, longer-term field trials, of at least two years, would further identify changes in the importance of different plant traits at various periods of cover crop usage. For instance, it may take a couple of years for the impact of root diameter on soil porosity to become apparent. Furthermore, it is hypothesised that below ground traits would increase in importance when above ground biomass is removed during the drier months.

Moreover, a longer term assessment of the transfer of nutrients from cover crops, to the soil and eventually to the olive and orange trees, such as those by

Buresh and Tian (1997) and Craswell (1997) crops such as coffee and banana, could be conducted to build on the findings in Chapter 3. In order to address concerns and contradictions in competition for water a detailed examination of water use and storage by cover crops in the field would be ideal. This could allow for the identification of plant traits which promote the storage of ground water (such as tap roots promoting infiltration). Also, an investigation into plant traits to prevent evaporation of dew and rain (such as above ground biomass) would be novel research and allay farmers worries. Working closely with farmers, and ensuring the findings of any more research conducted in this area of sustainable agriculture is necessary for farmers to make informed decisions.

This thesis has confirmed the importance of plant cover to control soil erosion, as a potentially cheaper, less intensive and effective means of soil conservation compared to tillage or herbicide. The knowledge of plant traits of common species to grow in hillside orchards in Spain has been expanded. The complexities of plant traits within a mix with a dominant legume have been explored and avenues for future research have been opened.

7. References

Abrisqueta, J. M., Plana, V., Mounzer, O. H., Mendez, J. & Ruiz-Sánchez, M. C. (2007) Effects of soil tillage on runoff generation in a Mediterranean apricot orchard. *Agricultural Water Management,* 93(1)**,** 11-18.

Abu-Zreig, M., Rudra, R. P., Whiteley, H. R., Lalonde, M. N. & Kaushik, N. K. (2003) Phosphorus removal in vegetated filter strips. *Journal of Environmental Quality,* 32(2)**,** 613-619.

Amate, J. I., De Molina, M. G., Vanwalleghem, T., Fernández, D. S. & Gómez, J. A. (2013) Erosion in the Mediterranean: The Case of Olive Groves in the South of Spain (1752–2000). *Environmental history,* 18(2)**,** 360-382.

Angers, D. & Caron, J. (1998) Plant-induced Changes in Soil Structure: Processes and Feedbacks. *Biogeochemistry,* 42(1)**,** 55-72.

Araya, S. N., Mitchell, J. P., Hopmans, J. W. & Ghezzehei, T. A. (2022) Long-term impact of cover crop and reduced disturbance tillage on soil pore size distribution and soil water storage. *Soil,* 8(1)**,** 177.

Bailey, T., Robinson, N., Farrell, M., Macdonald, B., Weaver, T., Antille, D. L., Chin, A. & Brackin, R. (2022) Storage of soil samples leads to over-representation of the contribution of nitrate to plant-available nitrogen. *Soil research (Collingwood, Vic.),* 60(1)**,** 22.

Bardgett, R. D., Mommer, L. & De Vries, F. T. (2014) Going underground: root traits as drivers of ecosystem processes. *Trends in Ecology & Evolution,* 29(12)**,** 692-699.

Basche, A. & Delonge, M. (2017) The Impact of Continuous Living Cover on Soil Hydrologic Properties: A Meta-Analysis. *Soil Science Society of America journal,* 81(5)**,** 1179-1190.

Baumert, V. L., Vasilyeva, N. A., Vladimirov, A. A., Meier, I. C., Kögel-Knabner, I. & Mueller, C. W. (2018) Root exudates induce soil macroaggregation facilitated by fungi in subsoil. *Frontiers in environmental science,* 6.

Baxendale, C., Orwin, K. H., Poly, F., Pommier, T. & Bardgett, R. D. (2014) Are plant-soil feedback responses explained by plant traits?(Report). 204(2)**,** 408.

Bednar-Fridl, B., Biesbroek, R., Schmidt, D. N., Alexander, P., Børsheim, K. Y., Carnicer, J., Georgopulou, E., Haasnoot, M., Le Cozannet, G., Lionello, P., Lipka, O., Möllmann, C, Muccione, V., Mustonen, T., Piepenburg, D. & Whitmarsh, L. (2022) Europe. In: H.-O. Pörtner, D. C. R., M. Tignor, & E.S. Poloczanska, K. M., A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.) *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, USA: Cambridge University Press.

Benlhabib, O., Yazar, A., Qadir, M., Lourenço, E. & Jacobsen, S. E. (2014) How Can We Improve Mediterranean Cropping Systems? *J Agro Crop Sci,* 200(5), 325-332.

Besnard, G., Terral, J.-F. & Cornille, A. (2018) On the origins and domestication of the olive: a review and perspectives (vol 121, pg 385, 2018). *Ann Bot,* 121(3), 587-588.

Bochet, E., Poesen, J. & Rubio, J. L. (2006) Runoff and soil loss under individual plants of a semi-arid Mediterranean shrubland: influence of plant morphology and rainfall intensity. *Earth Surf. Process. Landforms,* 31(5), 536-549.

Bodner, G., Loiskandl, W. & Kaul, H. P. (2007) Cover crop evapotranspiration under semi-arid condition using FAO dual crop coefficient method with water stress compensation. *Agricultural Water Management,* 93, 85-98.

Borrelli, P., Poesen, J., Vanmaercke, M., Ballabio, C., Hervás, J., Maerker, M., Scarpa, S. & Panagos, P. (2021) Monitoring gully erosion in the European Union: A novel approach based on the Land Use/Cover Area frame survey (LUCAS). *International Soil and Water Conservation Research*.

Brevik, E. C. & Hartemink, A. E. (2010) Early soil knowledge and the birth and development of soil science. *Catena,* 83(1), 23-33.

Bronick, C. J. & Lal, R. (2005) Soil structure and management: a review. *Geoderma,* 124(1), 3-22.

Buitenhuis, Y., Candel, J. J. L., Termeer, K. J. A. M. & Feindt, P. H. (2022) Reconstructing the farming of resilience in the European Union's COmmon Agriculutral Policy post-2020 reform. *Journal of the European Society for Rural Sociology*.

Buresh, R. & Tian, G. (1997) Soil improvement by trees in sub-Saharan Africa. *An International Journal incorporating Agroforestry Forum,* 38(1)**,** 51-76.

Burylo, M., Rey, F., Bochet, E. & Dutoit, T. (2012) Plant functional traits and species ability for sediment retention during concentrated flow erosion. *An International Journal on Plant-Soil Relationships,* 353(1-2)**,** 135-144.

Calatrava, J. & Franco, J. A. (2011) Using pruning residues as mulch: Analysis of its adoption and process of diffusion in Southern Spain olive orchards. *Journal of Environmental Management,* 92(3)**,** 620-629.

Calatrava, J., Martínez-Granados, D., Zornoza, R., González-Rosado, M., Lozano-García, B., Vega-Zamora, M. & Gómez-López, M. D. (2021) Barriers and opportunities for the implementation of sustainable farming practices in mediterranean tree orchards. *Agronomy (Basel),* 11(5)**,** 821.

Calatrava Leyva, J. U. P. D. C. E. T. S. D. I. A., Franco Martínez, J. A. & González Roa, M. C. (2007) Analysis of the adoption of soil conservation practices in olive groves: the case of mountainous areas in Southern Spain. *Spanish journal of agricultural research : SJAR,* 5(3)**,** 249-258.

Cantón, Y., Solé-Benet, A., De Vente, J., Boix-Fayos, C., Calvo-Cases, A., Asensio, C. & Puigdefábregas, J. (2011) A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. *Journal of Arid Environments,* 75(12)**,** 1254-1261.

Cardinali, A., Carletti, P., Nardi, S. & Zanin, G. (2014) Design of riparian buffer strips affects soil quality parameters. *Applied Soil Ecology,* 80(C).

Castro, G. (2004) *La cubierta vegetal en el olivar: determinación experimental del uso del agua y*

de su influencia sobre los procesos de escorrentía y erosion.

Cecchini, M., Zambon, I., Pontrandolfi, A., Turco, R., Colantoni, A., Mavrakis, A. & Salvati, L. (2018) Urban sprawl and the ‘olive’ landscape: sustainable land management for ‘crisis’ cities. *GeoJournal,* 84(1)**,** 237-255.

Cerdà, A., Franch-Pardo, I., Novara, A., Sannigrahi, S. & Rodrigo-Comino, J. (2021) Examining the Effectiveness of Catch Crops as a Nature-Based Solution to Mitigate Surface Soil and Water Losses as an Environmental Regional Concern. *Earth systems and environment,* 6(1)**,** 29-44.

Cerdà, A. & Jurgensen, M. F. (2008) The influence of ants on soil and water losses from an orange orchard in eastern Spain. *Journal of applied entomology (1986),* 132(4)**,** 306-314.

Cerdà, A. & Rodrigo-Comino, J. (2021) Regional farmers' perception and societal issues in vineyards affected by high erosion rates. *Land (Basel),* 10(2)**,** 1-18.

Cerdà, A., Rodrigo-Comino, J., Giménez-Morera, A. & Keesstra, S. D. (2018) Hydrological and erosional impact and farmer's perception on catch crops and weeds in citrus organic farming in Canyoles river watershed, Eastern Spain. *Agriculture, ecosystems & environment,* 258**,** 49-58.

Chen, L.-L., Yuan, P., You, M.-S., Pozsgai, G., Ma, X., Zhu, H. & Yang, G. (2019) Cover Crops Enhance Natural Enemies While Help Suppressing Pests in a Tea Plantation. *Annals of the Entomological Society of America,* 112(4)**,** 348-355.

Commission, E. (2020) Reinforcing Europes resilience: halting biodiversity loss and building a healthy and sustainable food system. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_884.

Commission, E. (2022) *Status of glyphosate in the EU* [Online]. https://food.ec.europa.eu/plants/pesticides/approval-active-substances/renewal-approval/glyphosate_en: European Commission. [Accessed 27/02/22 2022].

Cornelissen, J., H, C, Lavorel, S., Garnier, E., Diaz, S., Buchmann, N., Gurvich, D., E, Reich, P., B, Ter Steege, H., Morgan, H., D, Van Der Heijden, M., G, A, Pausas, J., G & Poorter, H. (2003) A handbook of protocols for standardised and easy meaurement of plant functional traits worldwide. *Australian Journal of Botany,* 51**,** 335-380.

Craswell, E., Sajjapongse, A., Howlett, D. & Dowling, A. (1997) Agroforestry in the management of sloping lands in Asia and the Pacific. *An International Journal incorporating Agroforestry Forum,* 38(1)**,** 121-137.

Dabney, G. H., Dunn, S. M. & Dabney, S. M. (1996) Modulus of elasticity and moment of inertia of grass hedge stems. *Transactions of the American Society of Agricultural Engineers,* 39(3)**,** 947-952.

Dabney, S. M., Moore, M. T. & Locke, M. A. (2006) INTEGRATED MANAGEMENT OF IN-FIELD, EDGE-OF-FIELD, AND AFTER-FIELD

BUFFERS 1. *JAWRA Journal of the American Water Resources Association,* 42(1)**,** 15-24.

De Baets, S., Poesen, J., Gyssels, G. & Knapen, A. (2006) Effects of grass roots on the erodibility of topsoils during concentrated flow. *Geomorphology,* 76(1)**,** 54-67.

De Baets, S., Poesen, J., Knapen, A., Barberá, G. & Navarro, J. (2007a) Root characteristics of representative Mediterranean plant species and their erosion-reducing potential during concentrated runoff. *An International Journal on Plant-Soil Relationships,* 294(1)**,** 169-183.

De Baets, S., Poesen, J., Knapen, A. & Galindo, P. (2007b) Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. *Earth Surface Processes and Landforms,* 32(9)**,** 1323-1345.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J. (2009) Methodological framework to select plant species for controlling rill and gully erosion: application to a Mediterranean ecosystem. *Earth Surface Processes and **L**andforms* 34**,** 1374 - 1392.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., Baerdemaeker, J. & Muys, B. (2008) Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *An International Journal on Plant-Soil Relationships,* 305(1)**,** 207-226.

De Graaff, J., Kessler, A. & Olsen, P. (2010) Farm-level adoption of soil and water conservation measures and policy implications in Europe. *Land Use Policy,* 27(1)**,** 1-3.

Devices, D.-T. (2017) *ML3 User Manual Version 2.1* [Online]. Available at: https://delta-t.co.uk/wp-content/uploads/2017/02/ML3-user-manual-version-2.1.pdf [Accessed 07/06/21 2021].

Doetterl, S., Van Oost, K. & Six, J. (2012) Towards constraining the magnitude of global agricultural sediment and soil organic carbon fluxes. *Earth Surface Processes and Landforms,* 37(6)**,** 642-655.

Durán Zuazo, V. H., Martínez, J. R. F., Pleguezuelo, C. R. R., Martínez Raya, A. & Rodríguez, B. C. (2006) Soil-erosion and runoff prevention by plant covers in a mountainous area (se spain): Implications for sustainable agriculture. *The Environmentalist,* 26(4)**,** 309-319.

Eardley, F. (2022) Rising cost of agricultural fertiliser and feed: Causes, impacts and government policy. *In Focus*.

Ec (2020) Caring for Soil is Caring for Life. European Commission.

Eurostat (2021) Estimated soil erosion by water - area affected by severe erosion rate. European Commission - Joint Reserach Centre.

Eurostat, N. (2022) Mineral fertiliser consumption remained high in 2020. *Products Eurostat News*.

Fao (2019) Soil erosion: the greatest challenge to sustainable soil management. Rome.

Fao & Itps (2015) Status of the World's Soil Resources (SWSR) – Main Report. . Rome, Italy: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils.

Faostat. (2022) *Commodities by country* [Online]. https://www.fao.org/faostat/en/#rankings/commodities_by_country: FAOSTAT. [Accessed 15/06/22 2022].

Fernandez, A. L., Sheaffer, C. C., Wyse, D. L., Staley, C., Gould, T. J. & Sadowsky, M. J. (2016) Associations between soil bacterial community structure and nutrient cycling functions in long-term organic farm soils following cover crop and organic fertilizer amendment. *Sci Total Environ,* 566-567**,** 949-959.

Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N. & Kalantari, Z. (2022) Soil degradation in the European Mediterranean region: Processes, status and consequences. *The Science of the total environment,* 805**,** 150106-150106.

Finney, D. M., White, C. M. & Kaye, J. P. (2016) Biomass Production and Carbon/ Nitrogen Ratio Influence Eco system Services from Cover Crop Mixtures. *Agronomy journal,* 108(1)**,** 39-52.

Fox, A., Lüscher, A. & Widmer, F. (2020) Plant species identity drives soil microbial community structures that persist under a following crop. *Ecology and evolution,* 10(16)**,** 8652-8668.

Francia Martínez, J. R., Durán Zuazo, V. H. & Martínez Raya, A. (2006) Environmental impact from mountainous olive orchards under different soil-management systems (SE Spain). *Science of the Total Environment,* 358(1)**,** 46-60.

Freschet, G. T., Valverde-Barrantes, O. J., Tucker, C. M., Craine, J. M., Mccormack, M. L., Violle, C., Fort, F., Blackwood, C. B., Urban-Mead, K. R., Iversen, C. M., Bonis, A., Comas, L. H., Cornelissen, J. H. C., Dong, M., Guo, D., Hobbie, S. E., Holdaway, R. J., Kembel, S. W., Makita, N., Onipchenko, V. G., Picon-Cochard, C., Reich, P. B., Riva, E. G., Smith, S. W., Soudzilovskaia, N. A., Tjoelker, M. G., Wardle, D. A. & Roumet, C. (2017) Climate, soil and plant functional types as drivers of global fine-root trait variation. *Journal of Ecology,* 105(5)**,** 1182-1196.

García-Díaz, A., Bienes, R., Sastre, B., Novara, A., Gristina, L. & Cerdà, A. (2017) Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain. *Agriculture, ecosystems & environment,* 236**,** 256-267.

García-Ruiz, J. M. (2010) The effects of land uses on soil erosion in Spain: A review. *Catena,* 81(1)**,** 1-11.

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta–Martínez, T. & Beguería, S. (2011) Mediterranean water resources in a global change scenario. *Earth-science reviews,* 105(3)**,** 121-139.

García-Ruiz, J. M. & Valero-Garcés, B. L. (1998) Historical Geomorphic Processes and Human Activities in the Central Spanish Pyrenees. *Mountain Research and Development,* 18(4)**,** 309-320.

Ghestem, M., Cao, K., Ma, W., Rowe, N., Leclerc, R., Gadenne, C. & Stokes, A. (2014) A framework for identifying plant species to be used as 'ecological engineers' for fixing soil on unstable slopes. *PLoS ONE,* 9(8)**,** e95876.

Gonzalez-Sanchez, E. J., Veroz-Gonzalez, O., Blanco-Roldan, G. L., Marquez-Garcia, F. & Carbonell-Bojollo, R. (2015) A renewed view of conservation agriculture and its evolution over the last decade in Spain. *Soil & tillage research,* 146**,** 204-212.

Goodman, A. M., Crook, M. J. & Ennos, A. R. (2001) Anchorage Mechanics of the Tap Root System of Winter-sown Oilseed Rape (Brassica napus L.). *Ann Bot,* 87(3)**,** 397-404.

Gould, I. J., Quinton, J. N., Weigelt, A., De Deyn, G. B. & Bardgett, R. D. (2016) Plant diversity and root traits benefit physical properties key to soil function in grasslands. *Ecology Letters,* 19(9)**,** 1140-1149.

Gucci, R., Caruso, G., Bertolla, C., Urbani, S., Taticchi, A., Esposto, S., Servili, M., Sifola, M. I., Pellegrini, S., Pagliai, M. & Vignozzi, N. (2012) Changes of soil properties and tree performance induced by soil management in a high-density olive orchard. *European journal of agronomy,* 41**,** 18-27.

Gyssels, G. & Poesen, J. (2003) The importance of plant root characteristics in controlling concentrated flow erosion rates. *Earth Surface Processes and Landforms,* 28(4)**,** 371-384.

Gyssels, G., Poesen, J., Bochet, E. & Li, Y. (2005) Impact of plant roots on the resistance of soils to erosion by water: a review. *Progress in Physical Geography,* 29(2)**,** 189-217.

Gómez, J., Campos, M., Guzmán, G., Castillo-Llanque, F., Vanwalleghem, T., Lora, Á. & Giráldez, J. (2018) Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. *Environmental Science and Pollution Research,* 25(2)**,** 977-989.

Gómez, J. A. (2005) Effects of soil management on soil physical properties and infiltration in olive orchards - implications for yield. In: Organisation, F. A. A. (ed.) *Integrated soil and water management for orchard development.* Rome, FAO: FAO Land and Water Bulletin, 10.

Gómez, J. A. (2017) Sustainability using cover crops in Mediterranean tree crops, olives and vines – Challenges and current knowledge. *Hungarian Geographical Bulletin,* 66(1)**,** 13-28.

Gómez, J. A., Guzmán, M. G., Giráldez, J. V. & Fereres, E. (2009a) The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. *Soil & Tillage Research,* 106(1)**,** 137-144.

Gómez, J. A., Infante-Amate, J., González De Molina, M., Vanwalleghem, T., Taguas, E. V. & Lorite, I. (2014) Olive Cultivation, its Impact on Soil Erosion and its Progression into Yield Impacts in Southern Spain in the Past as a Key to a Future of Increasing Climate Uncertainty. *Agriculture,* 4(2)**,** 170-198.

Gómez, J. A., Montero, A. S., Guzmán, G. & Soriano, M.-A. (2021) In-depth analysis of soil management and farmers' perceptions of related risks in two olive grove areas in southern Spain. *International Soil and Water Conservation Research,* 9(3)**,** 461-473.

Gómez, J. A., Sobrinho, T. A., Giráldez, J. V. & Elías, F. (2009b) Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. *Soil and Tillage Research,* 102(1)**,** 5-13.

Hollander, N. G. D., Bastiaans, L. & Kropff, M. J. (2007) Clover as a cover crop for weed suppression in an intercropping design. II. Competitive ability of several clover species. *European journal of agronomy,* 26(2)**,** 104-112.

Hondebrink, M. A., Cammeraat, L. H. & Cerdà, A. (2017) The impact of agricultural management on selected soil properties in citrus orchards in Eastern Spain: A comparison between conventional and organic citrus orchards with drip and flood irrigation. *Sci Total Environ,* 581-582**,** 153-160.

Ipcc (2014) Europe. In: Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell & Soussana, J.-F. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, US: Cambridge University Press.

Iserloh, T., Ries, J. B., Gabriels, D. & Seeger, M. (2013) Rainfall simulations - constraints, needs and challenges for a future use in soil erosion research. *Zeitschrift für Geomorphologie,* 57(1)**,** 1-10.

Jahanzad, E., Barker, A. V., Hashemi, M., Eaton, T., Sadeghpour, A. & Weis, S. A. (2016) Nitrogen Release Dynamics and Decomposition of Buried and Surface Cover Crop Residues. *Agronomy journal,* 108(4)**,** 1735-1741.

Jang, W. S., Neff, J. C., Im, Y., Doro, L. & Herrick, J. E. (2021) The Hidden Costs of Land Degradation in US Maize Agriculture. *Earth's future,* 9(2)**,** n/a.

Jones, A., Panagos, P., Barcelo, S., Bouraoui, F., Bosco, C., Dewitte, O., Gardi, C., Erhard, M., Hervás, J., Hiederer, R., Jeffery, S., Lükewille, A., Marmo, L., Montanarella, L., Olazábal, C., Peterson, J.-E., Penizek, V., Strassburger, T., Tóth, G., Van Den Eeckhaut, M., Van Liedekerke, M., Verheijen, F., Viestova, E. & Yigini, Y. (2010) The State of Soil in Europe. *A contribution of the JRC to the European Environment Agency's Einivronment State and Outlook Report - SOER 2010.* European Enivironment Agency.

Jordan, A. & Martinez-Zavala, L. (2008) Soil loss and runoff rates on unpaved forest roads in southern Spain after simulated rainfall. *Forest ecology and management,* 255(3)**,** 913-919.

Keesstra, S., Pereira, P., Novara, A., Brevik, E. C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A. & Cerdà, A. (2016) Effects of soil management techniques on soil water erosion in apricot orchards. *Science of the Total Environment,* 551-552(C)**,** 357-366.

Keesstra, S. D., Rodrigo-Comino, J., Novara, A., Giménez-Morera, A., Pulido, M., Di Prima, S. & Cerdà, A. (2019) Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. *Catena (Giessen),* 174**,** 95-103.

Keller, B., Szabo, J., Centeri, C., Jakab, G. & Szalai, Z. (2018) Different land-use intensities and their susceptibility to soil erosion. *Agrochemistry and soil science*.

Kulmatiski, A., Beard, K. H. & Heavilin, J. (2012) Plant-soil feedbacks provide an additional explanation for diversity-productivity relationships. *Proceedings. Biological sciences,* 279(1740)**,** 3020.

Kurtzman, D., Shapira, R. H., Bar-Tal, A., Fine, P. & Russo, D. (2013) Nitrate fluxes to groundwater under citrus orchards in a Mediterranean climate: Observations, calibrated models, simulations and agro-hydrological conclusions. *J Contam Hydrol,* 151**,** 93-104.

Lavorel, S. & Garnier, E. (2002) Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. *Functional Ecology,* 16(5)**,** 545-556.

Lee, S.-M., Yun, H.-B., Gu, M., Sung, J.-K., An, N.-H., Lee, B.-M., Cho, J.-R., Jung, S.-K. & Choi, H.-S. (2014) Effects of hairy vetch, rye, and alternating cultivation of rye-vetch cover crops on soil nutrient concentrations and the production of red pepper (Capsicum annuum L.). *The journal of horticultural science & biotechnology,* 89(3)**,** 245-252.

Levy-Booth, D. J., Gulden, R. H., Campbell, R. G., Powell, J. R., Klironomos, J. N., Pauls, K. P., Swanton, C. J., Trevors, J. T. & Dunfield, K. E. (2009) Roundup Ready® soybean gene concentrations in field soil aggregate size classes. *FEMS Microbiol Lett,* 291(2)**,** 175-179.

Li, C. & Pan, C. (2018) The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of hydrology (Amsterdam),* 558**,** 90-103.

Liebman, A. M., Grossman, J., Brown, M., Wells, M. S., Reberg-Horton, S. C. & Shi, W. (2018) Legume Cover Crops and Tillage Impact Nitrogen Dynamics in Organic Corn Production. *Agronomy journal,* 110(3)**,** 1046-1057.

Loades, K. W., Bengough, A. G., Bransby, M. F. & Hallett, P. D. (2010) Planting density influence on fibrous root reinforcement of soils. *Ecological Engineering,* 36(3)**,** 276-284.

Lopez-Vicente, M. & Alvarez, S. (2018) Influence of DEM resolution on modelling hydrological connectivity in a complex agricultural catchment with woody crops. *Earth surface processes and landforms,* 43(7)**,** 1403-1415.

Mansour, D., Pérez-Hedo, M., Catalán, J., Karamaouna, F., Braham, M., Jaques, J. A. & Urbaneja, A. (2021) Biological control of the citrus leafminer 25 years after its introduction in the Valencia citrus growing area (Spain): A new player in the game. *Biological control,* 155**,** 104529.

Marques, M. J., Ramon, B., Joaquin, C., Ruiz-Colmenero, M., Barbero-Sierra, C. & Velasco, A. (2015) Analysing perception, attitudes and responses of winegrowers about sustainable land management in central Spain. *Land degradation and development,* 26**,** 438-4467.

Martínez-Murillo, J. F., Nadal-Romero, E., Regüés, D., Cerdà, A. & Poesen, J. (2013) Soil erosion and hydrology of the western Mediterranean badlands throughout rainfall simulation experiments: A review. *Catena (Giessen),* 106**,** 101-112.

Mauro, R., Anastasi, U., Lombardo, S., Pandino, G., Pesce, R., Alessia, R. & Mauromicale, G. (2015) Cover crops for managing weeds, soil chemical fertility and nutritional status of organically grown orange orchard in Sicily. *Ital. J. Agron.,* 10(2)**,** 101-104.

Mcneill, J. R. & Winiwarter, V. (2004) Breaking the sod: humankind, history, and soil. *Science (New York, N.Y.),* 304(5677)**,** 1627.

Montenegro, A. A. A., Abrantes, J. R. C. B., De Lima, J. L. M. P., Singh, V. P. & Santos, T. E. M. (2013) Impact of mulching on soil and water dynamics under intermittent simulated rainfall. *Catena (Giessen),* 109**,** 139-149.

Moore, M. T., Denton, D. L., Cooper, C. M., Wrysinski, J., Miller, J. L., Reece, K., Crane, D. & Robins, P. (2008) Mitigation assessment of vegetated drainage ditches for collecting irrigation runoff in California. *Journal of environmental quality,* 37(2)**,** 486.

Moreno-De-Las-Heras, M., Merino-Martín, L., Saco, P. M., Espigares, T., Gallart, F. & Nicolau, J. M. (2020) Structural and functional control of surface-patch to hillslope runoff and sediment connectivity in Mediterranean dry reclaimed slope systems. *Hydrology and earth system sciences,* 24(5)**,** 2855-2872.

Morgan, R. P. C. (2005) *Soil erosion and conservation.* 3rd ed. ed. Oxford: Blackwell Publishing.

Novara, A., Cerda, A., Barone, E. & Gristina, L. (2021) Cover crop management and water conservation in vineyard and olive orchards. *Soil & tillage research,* 208**,** 104896.

Olsen, S. R., Cole, C. V., Watanabe, F. S. & Dean, J. F. (1954) Estimation of Available Phosphorous in Soil by Extraction with Sodium Bicarbonate. *US Department of Agriculture Circular (1954)***,** 939.

Ovalle, C., Del Pozo, A., Peoples, M. B. & Lavín, A. (2010) Estimating the contribution of nitrogen from legume cover crops to the nitrogen nutrition of grapevines using a 15N dilution technique. *Plant and soil,* 334(1)**,** 247-259.

Ovalle, C., Urquiaga, S., Pozo, A. D., Zagal, E. & Arredondo, S. (2006) Nitrogen fixation in six forage legumes in Mediterranean central Chile. *Acta agriculturae Scandinavica. Section B, Soil and plant science,* 56(4)**,** 277-283.

Oñate, J. J. & Peco, B. (2005) Policy impact on desertification: stakeholders' perceptions in southeast Spain. *Land Use Policy,* 22(2)**,** 103-114.

Pacheco, F. A. L., Sanches Fernandes, L. F., Valle Junior, R. F., Valera, C. A. & Pissarra, T. C. T. (2018) Land degradation: Multiple environmental consequences and routes to neutrality. *Current opinion in environmental science & health,* 5**,** 79-86.

Palese, A. M., Vignozzi, N., Celano, G., Agnelli, A. E., Pagliai, M. & Xiloyannis, C. (2014) Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. *Soil & Tillage Research,* 144(C)**,** 96-109.

Panagos, P., Ballabio, C., Poesen, J., Lugato, E., Scarpa, S., Montanarella, L. & Borrelli, P. (2020) A soil erosion indicator for supporting agricultural, environmental and climate policies in the European union. *Remote sensing (Basel, Switzerland),* 12(9)**,** 1365.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L. & Alewell, C. (2015) The new assessment of soil loss by water erosion in Europe. *Environmental science & policy,* 54**,** 438-447.

Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C. & Crozier, C. (2014) Roller-Crimper Termination for Legume Cover Crops in North Carolina: Impacts on Nutrient Availability to a Succeeding Corn Crop. *Communications in soil science and plant analysis,* 45(8)**,** 1106-1119.

Pe'er, G., Dicks, L. V., Visconti, P., Arlettaz, R., Báldi, A., Benton, T. G., Collins, S., Dieterich, M., Gregory, R. D., Hartig, F., Henle, K., Hobson, P. R., Kleijn, D., Neumann, R. K., Robijns, T., Schmidt, J., Shwartz, A., Sutherland, W. J., Turbé, A., Wulf, F. & Scott, A. V. (2014) Agriculture policy. EU agricultural reform fails on biodiversity. *Science (New York, N.Y.),* 344(6188)**,** 1090.

Peoples, M., Ladha, J. & Herridge, D. (1995) Enhancing legume N 2 fixation through plant and soil management. *An International Journal on Plant-Soil Relationships,* 174(1)**,** 83-101.

Perez-Harguindeguy, N., Diaz, S., Garnier, E., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M., S, Cornwell, W., K, Craine, J., M, Gurvich, D., E, Urcelay, C., Veneklaas, E., J, Reich, P., B, Poorter, L., Wright, I., J, Ray, P., Enrico, L., Puasas, J., G, De Vos, A., C, Buchmann, N., Funes, G., Quetier, F., Hodgson, J., G, Thompson, K., Morgan, H., D, Ter Steege, H., Van Der Heijden, M., G, A, Sach, L., Blonder, B., Poschlod, P., Vaieretti, M., V, Conti, G., Staver, A., C, Aquino, S. & Cornelissen, J., H, C (2013) New handbook for standardised measurement of plant functional traits worldwide. *Australian Journal of Botany,* 61**,** 167-234.

Phillips, A. W., Reddy, S. & Durning, S. J. (2016) Improving response rates and evaluating nonresponse bias in surveys: AMEE Guide No. 102. *Med Teach,* 38(3)**,** 217-228.

Poesen, J., Nachtergaele, J., Verstraeten, G. & Valentin, C. (2003) Gully erosion and environmental change: importance and research needs. *Catena,* 50(2)**,** 91-133.

Pohl, M., Alig, D., Körner, C. & Rixen, C. (2009) Higher plant diversity enhances soil stability in disturbed alpine ecosystems. *An International Journal on Plant-Soil Relationships,* 324(1)**,** 91-102.

Qin, W., Assinck, F. B. T., Heinen, M. & Oenema, O. (2016) Water and nitrogen use efficiencies in citrus production: A meta-analysis. *Agriculture, ecosystems & environment,* 222**,** 103-111.

Quinton, J. N., Edwards, G. M. & Morgan, R. P. C. (1997) The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain. *Soil Use and Management,* 13(3)**,** 143-148.

Raese, J. T., Drake, S. R. & Curry, E. A. (2007) Nitrogen Fertilizer Influences Fruit Quality, Soil Nutrients and Cover Crops, Leaf Color and Nitrogen Content, Biennial Bearing and Cold Hardiness of 'Golden Delicious'. *Journal of plant nutrition,* 30(10)**,** 1585-1604.

Rallo, L., Diego, B., Castro-Garcia, S., Connor, D. J., Gomez-Del-Campo, M. & Rallo, R. (2013) High-Density Olive Plantations. *Horticultural Reviews,* 41**,** 303-384.

Ramón-Munoz, R. (2000) Specialization in the International Market for Olive Oil before World War II. In: Pamuk, S. & Williamson, J. G. (eds.) *The Mediterranean Response to Globablization before 1950.* London: Routledge.

Raya, A. M., Zuazo, V. H. D. & Martínez, J. R. F. (2006) Soil erosion and runoff response to plant-cover strips on semiarid slopes (SE Spain. *Land Degradation & Development,* 17(1)**,** 1-11.

Repullo-Ruibérriz De Torres, M. A., Ordónez-Fernández, R., Giráldez, J. V., Márquez-García, J., Laguna, A. & Carbonell-Bojollo, R. (2018) Efficiency of four different seeded plants and native vegetation as cover crops in the control of soil and carbon losses by water erosion in olive orchards. *Land Degradation and Development,* 29(8)**,** 2278-2290.

Rhymes, J. M., Cordero, I., Chomel, M., Lavallee, J. M., Straathof, A. L., Ashworth, D., Langridge, H., Semchenko, M., De Vries, F. T., Johnson, D. & Bardgett, R. D. (2021) Are researchers following best storage practices for measuring soil biochemical properties? *Soil,* 7(1)**,** 95-106.

Rochester, I. & Peoples, M. (2005) Growing vetches (Vicia villosa Roth) in irrigated cotton systems: inputs of fixed N, N fertiliser savings and cotton productivity. *Plant and soil,* 271(1/2)**,** 251-264.

Rodrigues, M., Dimande, P., Pereira, E., Ferreira, I., Freitas, S., Correia, C., Moutinho-Pereira, J. & Arrobas, M. (2015) Early-maturing annual legumes: an option for cover cropping in rainfed olive orchards. *(formerly Fertilizer Research),* 103(2)**,** 153-166.

Rodrigues, M. Â., Correia, C. M., Claro, A. M., Ferreira, I. Q., Barbosa, J. C., Moutinho-Pereira, J. M., Bacelar, E. A., Fernandes-Silva, A. A. & Arrobas, M. (2013) Soil nitrogen availability in olive orchards after mulching legume cover crop residues. *Scientia horticulturae,* 158**,** 45-51.

Rodrigues, M. Â., Lopes, J. I., Pavão, F. M., Cabanas, J. E. & Arrobas, M. (2011) Effect of Soil Management on Olive Yield and Nutritional Status of Trees in Rainfed Orchards. *Communications in soil science and plant analysis,* 42(9)**,** 993-1007.

Rogers, R. D. & Schumm, S. A. (1991) The effect of sparse vegetative cover on erosion and sediment yield. *Journal of Hydrology,* 123(1)**,** 19-24.

Rojo Serrano, L., Garcia Robredo, F., Martinez Artero, J. A. & Martinez Ruiz, A. (2002) Management Plan to Combat Desertification in the Guadalentin River Basin. In: Geeson, N. A., Brandt, C. J. & Thornes, J. B. (eds.) *Mediterranean Desertification: A Mosaic of Processes and Responses.* Chichester: Wiley.

Ruas, M.-P., Mane, P., Hallavant, C. & Lemonine, M. (2017) Citrus fruits in historical France: written sources, iconographic and plant remains. In: Zech-Matterne, V. & Fiorentino, G. (eds.) *ARGUMED: Archaeology and history of citrus fruit in the Mediterranean.* Publications du Centre Jean Bérard.

Ruiz-Colmenero, M., Bienes, R., Eldridge, D. J. & Marques, M. J. (2013) Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. *Catena,* 104(C), 153-160.

Ruiz-Colmenero, M., Bienes, R. & Marques, M. J. (2011) Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. *Soil & Tillage Research,* 117(C), 211-223.

Sainju, U. M., Whitehead, W. F. & Singh, B. P. (2005) Biculture Legume–Cereal Cover Crops for Enhanced Biomass Yield and Carbon and Nitrogen. *Agronomy journal,* 97(5), 1403-1412.

Salazar-Ordóñez, M., Rodríguez-Entrena, M. & Sayadi, S. (2011) Agricultural Sustainability from a Societal View: An Analysis of Southern Spanish Citizens. *Journal of agricultural & environmental ethics,* 26(2), 473-490.

Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M. & García-Díaz, A. (2017) Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. *Journal of Soils and Sediments,* 17(3), 873-888.

Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M. J. & García-Díaz, A. (2016) Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. *Journal of soils and sediments,* 17(3), 873-888.

Sastre, B., Álvarez, B., Antón, O., Pérez, M. Á., Marques, M. J., Bienes, R. & García-Díaz, A. (2020) Groundcovers in Olive Groves in Semiarid Climates: Are They Always Beneficial? *Water (Basel),* 12(8), 2230.

Schmidtke, A., Rottstock, T., Gaedke, U. & Fischer, M. (2010) Plant community diversity and composition affect individual plant performance. *Oecologia,* 164(3), 665-677.

Schneider, C. A., Rasband, W. S. & Eliceiri, K. W. (2012) NIH Image to ImageJ: 25 years of image analysis. *Nat Methods,* 9(7), 671-675.

Segovia, C., Gómez, J., Gallardo, P., Lozano, F. & Asensio, C. (2017) Soil nutrients losses by wind erosion in a citrus crop at southeast Spain. *Eurasian Soil Science,* 50(6), 756-763.

Snoeck, D., Zapata, F. & Domenach, A.-M. (2000) Isotopic evidence of the transfer of nitrogen fixed by legumes to coffee trees. *Biotechnologie, agronomie, société et environnement,* 4(2), 95-100.

Soriano, M. A., Cabezas, J. M., Ramos, A., Lora, A. & Gómez, J. A. (2016) Characterization of cover crops for use in olive groves and vineyards in certified systems under Meditarranean conditions. West Lafayette, IN: AgroEnvron 2016.

Sousa, A. A. R., Parra-López, C., Sayadi-Gmada, S., Barandica, J. M. & Rescia, A. J. (2020) Evaluation of the objectives and concerns of farmers to apply different agricultural managements in olive groves: The case of estepa region (southern, spain). *Land (Basel),* 9(10)**,** 1-21.

Spehn, E. M., Scherer-Lorenzen, M., Schmid, B., Hector, A., Caldeira, M. C., Dimitrakopoulos, P. G., Finn, J. A., Jumpponen, A., O'donnovan, G., Pereira, J. S., Schulze, E. D., Troumbis, A. Y. & Körner, C. (2002) The role of legumes as a component of biodiversity in a cross-European study of grassland biomass nitrogen. *Oikos,* 98(2)**,** 205-218.

Sssa (2008) Glossary of Soil Science Terms. Madison, WI: Soil Science Society of America.

Stevens, C. J., Quinton, J. N., Bailey, A. P., Deasy, C., Silgram, M. & Jackson, D. R. (2009) The effects of minimal tillage, contour cultivation and in-field vegetative barriers on soil erosion and phosphorus loss. *Soil & Tillage Research,* 106(1)**,** 145-151.

Taguas, E. V. & Gómez, J. A. (2015) Vulnerability of olive orchards under the current CAP (Common Agricultural Policy) regulations on soil erosion: a study case in Southern Spain. *Land Use Policy,* 42(C)**,** 683-694.

Thomas, E., Riley, M. & Spees, J. (2020) Knowledge flows: Farmers' social relations and knowledge sharing practices in 'Catchment Sensitive Farming1. *Land Use Policy,* 90.

Vanwalleghem, T., Amate, J. I., De Molina, M. G., Fernández, D. S. & Gómez, J. A. (2011) Quantifying the effect of historical soil management on soil erosion rates in Mediterranean olive orchards. *Agriculture, Ecosystems and Environment,* 142(3)**,** 341-351.

Vanwalleghem, T., Gómez, J. A., Infante Amate, J., González De Molina, M., Vanderlinden, K., Guzmán, G., Laguna, A. & Giráldez, J. V. (2017) Impact of historical land use and soil management change on soil erosion and agricultural sustainability during the Anthropocene. *ANTHROPOCENE,* 17**,** 13-29.

Verheijen, F. G. A., Jones, R. J. A., Rickson, R. J. & Smith, C. J. (2009) Tolerable versus actual soil erosion rates in Europe. *Earth-science reviews,* 94(1-4)**,** 23-38.

Wolpert, F., Quintas-Soriano, C. & Plieninger, T. (2020) Exploring land-use histories of tree-crop landscapes: a cross-site comparison in the Mediterranean Basin. *Sustainability science,* 15(5)**,** 1267-1283.

Wu, G. A., Prochnik, S., Jenkins, J., Salse, J., Hellsten, U., Murat, F., Perrier, X., Ruiz, M., Scalabrin, S., Terol, J., Takita, M. A., Labadie, K., Poulain, J., Couloux, A., Jabbari, K., Cattonaro, F., Del Fabbro, C., Pinosio, S., Zuccolo, A., Chapman, J., Grimwood, J., Tadeo, F. R., Estornell, L. H., Muñoz-Sanz, J. V., Ibanez, V., Herrero-Ortega, A., Aleza, P., Pérez-Pérez, J., Ramón, D., Brunel, D., Luro, F., Chen, C., Farmerie, W. G., Desany, B., Kodira, C., Mohiuddin, M., Harkins, T., Fredrikson, K., Burns, P., Lomsadze, A., Borodovsky, M., Reforgiato, G., Freitas-Astúa, J., Quetier, F., Navarro, L., Roose, M., Wincker, P., Schmutz, J., Morgante, M., Machado, M. A., Talon, M., Jaillon, O., Ollitrault, P., Gmitter, F. & Rokhsar, D. (2014) Sequencing of diverse mandarin, pummelo and orange genomes reveals complex history of admixture during citrus domestication. *Nat Biotechnol,* 32(7)**,** 656-662.

Wuepper, D. (2020) Does culture affect soil erosion? Empirical evidence from Europe. *European review of agricultural economics,* 47(2)**,** 619-653.

Xiao, B., Wang, Q.-H., Wu, J.-Y., Huang, C.-W. & Yu, D.-F. (2010) Protective function of narrow grass hedges on soil and water loss on sloping croplands in Northern China. *Agriculture, Ecosystems and Environment,* 139(4)**,** 653-664.

Yang, W., Feng, G., Adeli, A., Kersebaum, K. C., Jenkins, J. N. & Pinfang, L. (2019) Long-term effect of cover crop on rainwater balance components and use efficiency in the no-tilled and rainfed corn and soybean rotation system. *Agricultural Water Management,* 219**,** 27-39.

Zhu, H., Fu, B., Wang, S., Zhu, L., Zhang, L., Jiao, L. & Wang, C. (2015) Reducing soil erosion by improving community functional diversity in semi-arid grasslands. *Journal of Applied Ecology,* 52(4)**,** 1063-1072.

Zika, M. & Erb, K.-H. (2009) The global loss of net primary production resulting from human-induced soil degradation in drylands. *Ecological economics,* 69(2), 310-318.

Zuazo, V. & Pleguezuelo, C. (2008a) Soil-erosion and runoff prevention by plant covers. A review. *Agron. Sustain. Dev.,* 28(1), 65-86.

Zuazo, V. H. D. & Pleguezuelo, C. R. R. (2008b) Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for sustainable development,* 28(1), 65-86.

Zuazo, V. H. D., Pleguezuelo, C. R. R., Panadero, L. A., Raya, A. M., Martínez, J. R. F. & Rodríguez, B. C. (2009) Soil Conservation Measures in Rainfed Olive Orchards in South-Eastern Spain: Impacts of Plant Strips on Soil Water Dynamics. *Pedosphere,* 19(4), 453-464.

Appendix 1 Survey

Lancaster University

Español

Me llamo Helena Ripley, soy estudiante de doctorado en la Universidad de Lancaster en el Reino Unido. Estoy estudiando la erosión del suelo en cultivos leñosos españoles y el uso de cultivos de cobertura parareducirla. El objetivo del estudio es comprender las diferencias entre el costey la eficacia de los controles de la erosión del suelo. En colaboración con el Instituto de Agricultura Sostenible, CSIC, de Córdoba, y PrimaFruit. Porfavor, lea la siguiente información para ayudarle a decidir si desea participar.

¿De quése trata el estudio?

Esta breve encuesta me ayudará a comprender el alcance de la erosión del suelo en las cultivos leñosos en España. Me gustaría saber si los agricultores observan síntomas de erosión del suelo, qué medidas de conservación del suelo y del aguase utilizan y por qué se utilizan esas medidas. Le agradecería que tomara 10 minutos para completar esta encuesta.

¿Tengo que participar?

No está obligado a completar la encuesta y puede detenerse en cualquier momento. Si desea retirar su encuesta completada, envíe un correo electrónico a h.ripley1@lancaster.ac.uk la semana posterior a completarla. Una vez que se hayan recopilado y anonimizado todos los datos, no será posible eliminarlos. Sin embargo, cualquier cita directa puedeser eliminada hasta el punto de publicación.

¿Serán mis datos identificables?

No, cualquier dato de identificación, como las direcciones de correo electrónico,se almacenará de forma segura y separada de los demás datos. Es su elección proporcionar una dirección de correo electrónico, que sólo se utilizará para contactar con usted para participar en la investigación de este proyecto. Las direcciones de correo electrónico se eliminarán de todos los registros al finalizar el proyecto y no se compartirán con nadie fuera del grupo de investigación. Los datos serán anonimizados y cotejados antes de ser compartidos con nadie. Todos los datos se almacenarán de forma segura en archivos codificados de acuerdo con las directrices de la Universidad de Lancaster y la Ley de Protección de Datos del Reino Unido de 2018.

¿Cómo usaremos la información que ha compartido con nosotros y qué pasará con los resultados del estudio de investigación?

Utilizaré la información que me proporcione sólo con fines académicos; esto incluirá mi tesis doctoral y artículos de revistas. Puedo presentar los resultados de este estudio en conferencias académicas y de la industria. Al redactar los resultados de este estudio, me gustaría compartir algunos de los puntos de vista que usted declara en su encuesta. Sólo usaré citas anónimas para que no puedan ser identificados.

¿Quién ha revisado este proyecto?

Este proyecto ha sido aprobado por el comité de ética de investigación de la Facultad de Cienca y Tecnología de la Universidad de Lancaster. La fecha límite para completar y enviar la encuesta es junio de 2021.

¿Qué pasa si tengo una pregunta o preocupación?

Si tiene alguna pregunta sobre la encuesta, envíeme un correo electrónico a h.ripley1@lancaster.ac.uk o comuníquese con la supervisora del proyecto, la catedrático Carly Stevens en c.stevens@lancaster.ac.uk. Si tiene inquietudes sobre la encuesta, comuníquese con el director de Lancaster Environment Centre, el catedrático Phil Barker, en p.barker@lancaster.ac.uk.

Para obtener más información sobre cómo la Universidad de Lancaster procesa los datos personales con fines de investigación y sus derechos sobre los datos, visite www.lancaster.ac.uk/reserach/data-protection.

Gracias por considerar la posibilidad de participar en este proyecto.

Formulario de consentimiento

- Confirmo que heleído la información anterior y entiendo completamente lo que se espera de mídentro de este estudio. He tenido la oportunidad de hacer preguntas y obtenerrespuestas.
- Entiendo que miparticipación es voluntaria y que puedo retirarme en cualquier momento sin dar ningún motivo.
- Entiendo que lainformación que proporcione se combinará con las respuestas de otrosparticipantes, se anonimizará y podrá publicarse; Se tomarán todas las medidasrazonables para proteger el anonimato de los participantes involucrados en esteproyecto. Entiendo que una vez que mis datos hayan sido anonimizados yclasificados, la semana posterior a completarla, es posible que no se puedan retirar, aunquecualquier cita directa pueda ser eliminada hasta el punto de publicación
- Doy miconsentimiento para que la información y citas de mi entrevista se utilicen eninformes, conferencias y tesis doctorales.

- Entiendo que elinvestigador discutirá los datos con su supervisor según sea necesario.
- Entiendo quecualquier información que proporcione permanecerá confidencial y anónima amenos que se crea que existe un riesgo de daño para mí o para otros, en cuyocaso el investigador principal puede necesitar compartir esta información consu supervisor de investigación.

Al hacer clic aquí doy mi consentimiento para participar en este estudio.

→

Lancaster University

Español

¿Dónde está su explotación agrícola? Indique la ciudad o pueblo más cercanas y la región.

¿Qué tipo de explotación agrícola es?

Explotación agrícola familiar

Inquilino agricultor

¿Qué tipo de negocio es?

Propiedad

Alquilada

¿Cuántos años tiene usted?

Cuál es su género:

- Hombre
- Mujer
- Otro
- Prefiero no decirlo

¿Qué cultivos leñosos cultiva? Indique cuántas hectáreas tiene de cada tipo de cultivos leñosos y si es de regadío.

- Naranjas
- Olivos
- Almendros
- Fruta con hueso
- Otro (por favor especifique)
- Otro (por favor especifique)

Otro (por favor especifique)

Otro (por favor especifique)

¿Cuál es el tamaño total de su explotación agrícola? (hectáreas de todas las parcelas de leñosos que cultiva)

¿Cuántas fincas (o parcelas separadas y situadas en diferentes zonas) tiene?

¿Cuánto tiempo lleva cultivando leñosos? (años)

¿Ha notado alguna de los sintomas sintomas en su explotación agrícola? Marque todas las que correspondan:

Riachuelos o barrancos

Deposición de sedimentos

El suelo cambia de color

Aumento de la compactación del suelo

Cambios en la profundidad del suelo

Aumento de la pedregosidad

Otro (por favor especifique)

Ninguno

No lo sé

¿Encuántos de sus parcela ha observado estas características?

¿Cuántos campos tienen una inclinación superior al 10%?

¿Cree que la erosión del suelo le está haciendo perder rendimiento?

¿Por qué crees esto?

¿Toma medidas para conservar el suelo y el agua?

Sí

No

Anterior

Siguiente

¿Cómo controla la erosión del suelo? Marque todas las que correspondan.

- Terrazas
- Residuos de mantilla/ poda
- Labranza
- Cubierta vegetal
- Otro (por favor especifique)
- No lo sé

¿Cuánto tiempo lleva usando este método? (años)

¿Cuáles son las razones por las que utiliza sus métodos actuales de control de la erosión? Marque todas las que correspondan.

- Tradición
- Opción más barata
- Recomendado por compañeros agrícolas
- Recomendado por un agrónomo
- Recomendado por una revista de agricultura
- Recomendado en la radio
- Recomendado en un podcast

Recomendado en un podcast

Recomendado en TV

Recomendado por una universidad o instituto de investigación

Recomendado en un grupo o evento agrícola

Recomendado por el gobierno

Otro (por favor especifique)

¿Usa cubierta vegetal?

Sí

No

Anterior Siguiente

Si usa cubierta vegetal, qué tipo usa. Marque todas las que correspondan:

- Espontáneo/ malezas
- Plantado
- Mezcla de los dos
- No lo sé

¿Cómo eligió lo que plantó?

Anterior

Siguiente

Lancaster University

Español

Clasifique los siguientes medidas de controles de erosión del suelo con la efectividad que cree que tienen. (El más efectivo es 1, el menos efectivo es 6.)

	1	2	3	4	5	6
Terrazas	☐	☐	☐	☐	☐	☐
Residuos de mantillo/ poda	☐	☐	☐	☐	☐	☐
Labranza	☐	☐	☐	☐	☐	☐
Cubierta vegetal espontáneo	☐	☐	☐	☐	☐	☐
Cubierta vegetal plantado	☐	☐	☐	☐	☐	☐
Otro (por favor especifique)	☐	☐	☐	☐	☐	☐

¿Cuál estima que es el coste del método anual por hectárea? Si no cree que puede estimarlo, déjelo en blanco.

Construcción de terrazas	
Mantenimiento de terrazas	
Residuos de mantilla/ poda	
Labranza	
Cubierta vegetal espontáneo	
Cubierta vegetal plantado	
Otro (por favor especifique)	
Otro (por favor especifique)	
Otro (por favor especifique)	

¿Qué efectos cree que tienen las cubiertas vegetal en los cultivos comerciales? Marque todas las que correspondan.

	Incrementar	Ningún cambio	Disminución
Disponibilidad de agua	○	○	○
Nutrientes	○	○	○
La erosión del suelo	○	○	○
Otro (por favor especifique)	○	○	○

¿Cuálesson las barreras para implementar métodos de control de la erosión? Marque todas las que correspondan.

- El coste de cambiar o comenzar un nuevo método
- Falta de conocimiento sobre qué métodos son más efectivos.
- Sabe que métodos son efectivos, pero no sabe suficiente sobre como implementarlos
- Por la disminucíon
- Otro (por favor especifique)

Anterior Siguiente

English translation

My name is Helena Ripley, I am a PhD student at Lancaster University in the UK. I am studying soil erosion in Spanish orchards and the use of cover crops to reduce it. The aim of the study is to understand the differences between the cost and effectiveness of soil erosion controls. In collaboration with the Institute of Sustainable Agriculture, CSIC, and Primafruit. Please read the following information to help you to decide whether to take part in the study.

What is the study about?

This short survey will help me to understand the extent of soil erosion in tree crop farms in Spain. I would like to know whether farmers experience soil erosion, which soil and water conservation measures are used and why those measure are used. I would be grateful if you could take 10 minutes to complete this survey.

Do I have to participate?

You are not obliged to complete the survey and can stop at any time. If you wish to withdraw your completed survey please send an email to h.ripley1@lancaster.ac.uk within one week of completion. Once all the data has been collected and anonymised it will not be possible to delete it. However, any direct quotes can be removed up to the point of publication.

Will my data be identifiable?

No, any identifying data, such as email addresses, will be stored securing and separately to the other data. It is your choice to provide an email address, which will only be used to contact you to further participate in the research of this project. Email addresses will be deleted from all records at the completion of the project and will not be shared with anyone outside the research group. Data will be anonymised and collated before it is shared with anyone. All data will be stored securely in encrypted files in line with Lancaster University guidelines, and the UK Dara Protection Act 2018.

How will we use the information you have shared with us and what will happen to the result of the research study?

I will use the information you provide for academic purposes only; this will include my PhD thesis and journal articles. I may present the findings of this study at academic and industry conferences. When writing up the findings of this study, I would like to share some of the views you state in your survey. I will only use anonymised quotes so that you cannot be identified.

Who has reviewed this project?

This project has been approved by the Faculty of Science and Technology Research Ethics Committee. The deadline for the completion and submission of the survey is April 2021.

What if I have a question or concern?

If you have any questions about the survey please email me at h.ripley1@lancaster.ac.uk or contact the project supervisor Professor Carly Steven at c.stevens@lancaster.ac.uk. If you have concerns about the survey please contact the Head of Lancaster Environment Centre Professor Phil Barker at p.barker@lancaster.ac.uk.

For further information about how Lancaster University processes personal data for research purposes and your data rights, please visit www.lancaster.ac.uk/reserach/data-protection.

Thank you for considering to participate in this project.

Consent form

- I confirm that I have read the information above and fully understand what is expected of me within this study. I have had the opportunity to ask questions and to have them answered.
- I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.
- I understand that the information I provide will be pooled with other participants' responses, anonymised and may be published; all reasonable steps will be taken to protect the anonymity of the participants involved in this project. I understand that once my data have been anonymised and sorted, one week after submission, it may not be possible for it to be withdrawn, though direct quotes can be removed if required, up to the point of publication.
- I consent to information and quotations from my interview being used in reports, conferences and PhD thesis.
- I understand that the researcher will discuss data with their supervisor as needed.
- I understand that any information I give will remain confidential and anonymous unless it is thought that there is a risk of harm to myself or others, in which case the principal investigator may need to share this information with their research supervisor.

I consent to take part in this study (this answer is required to continue)

1. Where is your farm? Nearest town __________ Region __________

2. What type of farm is it?
    a. Family farm
    b. Tenant farmer
3. Is the farm:
    c. Owned
    d. Rented
3. What is your age? __________
4. What is your gender:
    a. Male
    b. Female
    c. Other
    d. Prefer not to say
5. Which tree crops do you farm?
    a. Oranges
    b. Olives
    b. Almonds
    c. Stone fruit
    d. Other (please specify) __________
    e. Other (please specify) __________
    f. Other (please specify) __________
    g. Other (please specify) __________
6. What is the total size of your farm? (Hectares of all the parcels of land you cultivate) _________
7. How many fields (or separate plots of land located in different areas) do you have? _________
8. How long have there been tree crops on the farm? (years) _______
9. Have you noticed any of the following features on your farm? Tick all that apply
    a. Rills or gullies
    b. Sediment deposition
    c. Soil changing colour
    d. Increase in compaction of the soil
    e. Changes in soil depth

f. Increase in stoniness
g. Other (please specify) _________
h. None
i. Don't know

10. In how many of your plots have you observed these characteristics? _________

11. How many fields have slopes above 10%?
12. Do you think that soil erosion cause you to lose yield?
13. Why do you think this?
1. Do you take measures to conserve soil and water? (conditional)
   a. Yes
   b. No
14. How do you control soil erosion? Tick all that apply
   a. Terraces
   b. Mulch/ pruning residue
   c. Tillage
   d. Cover crop
   e. None
   f. Other (please specify)
   g. Don't know
15. How long have you used this method? ________ years
21. What are the reasons you use your current methods of erosion control? (tick all that apply) (Conditional on using erosion control)
   a. Tradition
   b. Cheapest option
   c. Recommended by farming friends
   d. Recommended by agronomist
   e. Recommended in farming magazine
   f. Recommended on the radio
   g. Recommended on a podcast
   h. Recommended on TV
   i. Recommended by university or research institute
   j. Recommended in a focus group/ farming event
   k. Recommended by government

l. Other (please specify)

16. If you use cover crops are they: (tick all that apply)
    a. Spontaneous/ weeds
    b. Planted
    c. Mix of the two
    d. Don't know
17. If you planted cover crops, how did you choose what you planted?
Written response
18. Please rank the following soil erosion controls according to how effective you think they are (most effective is 1, least effective is 7).
    a. Terraces
    b. Mulch/ pruning residue
    c. Tillage
    d. Spontaneous cover crop
    e. Planted cover crop
    f. Other (Please specify) _________
19. Please could you include as estimate for how much you think each method would cost per year (€/ha). If you don't feel able to estimate, please leave blank.
    a. Construction of terraces
    b. Maintenance of terraces
    b. Mulch/ pruning residue
    c. Tillage
    d. Spontaneous cover crop
    e. Planted cover crop
    f. Other (Please specify) _________
    g. Other (Please specify) _________
    h. Other (Please specify) _________
20. What effects do you think cover crops could have on cash crops? Tick all that apply
    a. Water availability
    b. Nutrients
    c. Soil erosion
    d. Other (please specify)

22. What are the barriers to putting erosion control methods in place?
    a. Cost of changing/ starting new method
    b. Cost of continuing new method
    c. Lack of knowledge about which methods are more effective
    d. Know other methods are more effective but don't know enough about those methods
    e. Worried about lack of yield
    f. Other (please specify)
23. Would you be interested in taking part in a longer survey or interview? If so, please include your email address. This will be deleted from all records at the completion of the project.

Appendix 2 Questionnaire

Please can you read this explanation of why we are conducting this interview and what is expected from you.

Do you consent for the answers you give today to be recorded and used as outlined in the document? Your responses will be anonymised and not shared directly with Martinaavarro, Vicente Giner (Thursday only) or Primafruit.

Por favor, lea esta explicación de por qué estamos realizando esta entrevista y qué se espera de usted.

¿Da su consentimiento para que las respuestas que dé hoy sean grabadas y utilizadas como se indica en el documento? Sus respuestas serán anónimas y no se compartirán directamente con Martinaavarro, Vicente Giner (sólo el jueves) o Primafruit.

Me llamo Helena Ripley, soy estudiante de doctorado en la Universidad de Lancaster en el Reino Unido. Estoy estudiando la erosión del suelo en cultivos leñosos españoles y el uso de cultivos de cobertura parareducirla. El objetivo del estudio es comprender las diferencias entre el costey la eficacia de los controles de la erosión del suelo. En colaboración con el Instituto de Agricultura Sostenible, CSIC, de Córdoba, y PrimaFruit.

Porfavor, lea la siguiente información para ayudarle a decidir si desea participar.

¿De qué trata la entrevista?

Esta entrevista me ayudará a comprender el alcance de la erosión del suelo en los cultivos leñosos en España. Me gustaría conocer sus experiencias sobre la erosión del suelo, qué medidas de conservación del suelo y del agua utiliza y por qué. Además, me gustaría conocer su opinión sobre la gestión de la erosión del suelo y el apoyo disponible para los agricultores. Le agradecería que dedicara una hora a esta entrevista.

¿Qué se me pedirá que haga si participo?

Esta entrevista está semiestructurada, las preguntas son sobre su granja y cómo la gestiona. Algunas de las preguntas serán respuestas breves, mientras que en otras podrá ampliar su respuesta. Si desea recibir el resultado de la encuesta, facilite sus datos de contacto. Estos se utilizarán únicamente para este fin. No se compartirán y se eliminarán al final del proyecto.

¿Tengo que participar?

No está obligado a completar la entrevista y puede dejarla en cualquier momento. Si desea retirar los datos que ha proporcionado, envíe un correo electrónico a h.ripley1@lancaster.ac.uk antes del 1 de mayo de 2022. Una vez recogidos y anonimizados todos los datos, no será posible eliminarlos. Sin embargo, las citas directas pueden eliminarse hasta el momento de su publicación.

¿Serán mis datos identificables?

No, cualquier dato de identificación, como las direcciones de correo electrónico,se almacenará de forma segura y separada de los demás datos. Es su decisión proporcionar una dirección de correo electrónico, que sólo se utilizará para enviarle los resultados de esta investigación, si así lo desea. Las direcciones de correo electrónico se eliminarán de todos los registros al finalizar el proyecto y no se compartirán con nadie fuera del grupo de investigación. Los datos serán anonimizados y cotejados antes de ser compartidos con nadie. Todos los datos se almacenarán de forma segura en archivos codificados de acuerdo con las directrices de la Universidad de Lancaster y la Ley de Protección de Datos del Reino Unido de 2018.

¿Cómo usaremos la información que ha compartido con nosotros y qué pasará con los resultados del estudio de investigación?

Utilizaré la información que me proporcione sólo con fines académicos; esto incluirá mi tesis doctoral y artículos de revistas. Puedo presentar los resultados de este estudio en conferencias académicas y de la industria. Al redactar los resultados de este estudio, me gustaría compartir algunos de los puntos de vista que usted declara en su encuesta. Sólo usaré citas anónimas para que no puedan ser identificados.

¿Quién ha revisado este proyecto?

Este proyecto ha sido aprobado por el comité de ética de investigación de la Facultad de Cienca y Tecnología de la Universidad de Lancaster. La fecha límite para completar y enviar la encuesta es junio de 2021.

¿Qué pasa si tengo una pregunta o preocupación?

Si tiene alguna pregunta sobre la encuesta, envíeme un correo electrónico a h.ripley1@lancaster.ac.uk o comuníquese con la supervisora del proyecto, la catedrático Carly Stevens en c.stevens@lancaster.ac.uk. Si tiene inquietudes sobre la encuesta, comuníquese con el director de Lancaster Environment Centre, el catedrático Phil Barker, en p.barker@lancaster.ac.uk.

Para obtener más información sobre cómo la Universidad de Lancaster procesa los datos personales con fines de investigación y sus derechos sobre los datos, visite www.lancaster.ac.uk/reserach/data-protection.

Gracias por considerar la posibilidad de participar en este proyecto.

Formulario de consentimiento

- Confirmo que heleído la información anterior y entiendo completamente lo que se espera de mídentro de este estudio. He tenido la oportunidad de hacer preguntas y obtenerrespuestas.

- Entiendo que miparticipación es voluntaria y que puedo retirarme en cualquier momento sin dar ningún motivo.

- Entiendo que lainformación que proporcione se combinará con las respuestas de otrosparticipantes, se anonimizará y podrá publicarse; Se tomarán todas las medidasrazonables para proteger el anonimato de los participantes involucrados en esteproyecto. Entiendo que una vez que mis datos hayan sido anonimizados yclasificados, la semana posterior a completarla, es posible que no se puedan retirar, aunquecualquier cita directa pueda ser eliminada hasta el punto de publicación

- Doy miconsentimiento para que la información y citas de mi entrevista se utilicen eninformes, conferencias y tesis doctorales.

- Entiendo que elinvestigador discutirá los datos con su supervisor según sea necesario.

- Entiendo quecualquier información que proporcione permanecerá confidencial y anónima amenos que se crea que existe un riesgo de daño para mí o para otros, en cuyocaso el investigador principal puede necesitar compartir esta información consu supervisor de investigación.

Introductory questions

What is your age? (By decades – 20s, 30s etc)

How big is your farm?

How long have you been farming?

Do you own your farm or is it tenanted?

What crops do you farm? What do you grow?

Have you always farmed tree crops?

How long have tree crops been farmed here?

How are farming management decisions made on this farm?

Are you the decision maker?

Do you make decisions alone or with an agronomist, family or staff member?

Preguntas de introducción

1. ¿Cuál es su edad? (Por décadas: 20, 30, etc.)

2. ¿Qué tamaño tiene su granja?

3. ¿Cuánto tiempo lleva cultivando?

4. ¿Es dueño de su granja o está arrendada?

5. ¿Qué cultivos realiza? ¿Qué cultiva?

6. ¿Siempre ha cultivado árboles?

a. ¿Desde cuándo se cultivan aquí los árboles?

¿Cómo se toman las decisiones de gestión agrícola en esta explotación?

a. ¿Es usted quien toma las decisiones?

b. ¿Toma las decisiones solo o con un agrónomo, un familiar o un miembro del personal?

Soil erosion questions

Do you know how much of your land experiences soil erosion?

Are you confident that you can identify soil erosion on your farm?

How do you identify soil erosion?

How do you manage the area between trees?

What method is used for weed removal? (Herbicide/tillage/other)

How often do you remove weeds?

Preguntas sobre la erosión del suelo

8. ¿Sabe qué parte de su tierra sufre la erosión del suelo?

9. ¿Está seguro de poder identificar la erosión del suelo en su explotación?

10. ¿Cómo identifica la erosión del suelo?

11. ¿Cómo gestiona la zona entre los árboles?

a. ¿Qué método se utiliza para eliminar las malas hierbas? (Herbicida / labranza / otro)

b. ¿Con qué frecuencia elimina las malas hierbas?

Cover crop questions

Do you use vegetation cover to control soil erosion in your tree crops?

Do you use vegetation cover for any other reason?

What reason?

Do you use any other sort of vegetation erosion control (edge of field strips, riparian borders etc)?

If yes

How long have you used vegetation cover?

Were they used before you started farming here?

Why did you start using vegetation cover?

Are they planted or spontaneous?

Which species do you use?

How do you manage them (tillage/ herbicide/ let die off)?

Have you noticed any changes in your land since using cover crops?

If no

What are your reasons for not using vegetation cover?

Have you ever used vegetation cover?

Why did you stop?

Can cover crops work with the farming culture in Spain?

Do you receive financial support for soil erosion control?

Do you think it is enough?

Do you think that with adequate support soil erosion can be well managed?

Preguntas sobre los cultivos de cobertura

12. ¿Utiliza cubierta vegetal para controlar la erosión del suelo en sus cultivos arbóreos?

13. ¿Utiliza los cubierta vegetal por alguna otra razón?

a. ¿Qué razón?

14. ¿Utiliza algún otro tipo de control de la erosión por parte de la vegetación (franjas de borde de campo, bordes ribereños, etc.)?

15. En caso afirmativo

a. ¿Desde cuándo utiliza cubierta vegetal?

b. ¿Se utilizaban antes de empezar a cultivar aquí?

i. ¿Por qué empezó a utilizar cultivos de cobertura?

c. ¿Son plantados o espontáneos?

d. ¿Qué especies utiliza?

e. ¿Cómo las maneja (labranza/herbicida/dejar morir)?

f. ¿Has notado algún cambio en tu terreno desde que utilizas cultivos de cobertura?

16. En caso negativo

a. ¿Cuáles son las razones por las que no utiliza cubierta vegetal?

b. ¿Ha utilizado alguna vez cultivos de cobertura?

i. ¿Por qué dejó de hacerlo?

17. ¿Pueden los cultivos de cobertura funcionar con la cultura agrícola en España?

18. ¿Recibe ayudas económicas para el control de la erosión del suelo?

19. ¿Cree que es suficiente?

20. ¿Cree que con el apoyo adecuado se puede gestionar bien la erosión del suelo?

Reserve questions (ask if the topic is mentioned):

Water

Are you worried about the impact of vegetation cover on water availability for the tree crops?

Do you irrigate your tree crops?

If you use vegetation cover do you irrigate it?

Have you noticed a difference in tree crop yields or quality under different watering techniques?

Nutrients

Are you worried about the effect of cover crops on nutrient availability for tree crops?

Do you notice a change in tree crop yields under different inter row management techniques?

Do you use any fertilisers or nutrient inputs on your tree crops?

Do you use any fertilisers or nutrient inputs on your cover crops?

Cost

How could this be overcome (subsidies, cheaper seeds etc)?

How does the cost compare to other management practices such as tillage or herbicide?

Do you think more people would use cover crops if the cost was lower?

Why is it too expensive?

Preguntas de reserva (pregunte si se menciona el tema):

Agua

23. ¿Le preocupa el impacto de los cultivos de cobertura en la disponibilidad de agua para los cultivos arbóreos?

24. ¿Riega sus cultivos arbóreos?

25. Si utiliza cultivos de cobertura, ¿los riega?

26. ¿Has notado alguna diferencia en el rendimiento o la calidad de los cultivos de cobertura con diferentes técnicas de riego?

Nutrientes

27. ¿Le preocupa el efecto de los cultivos de cobertura en la disponibilidad de nutrientes para los cultivos arbóreos?

28. ¿Nota algún cambio en el rendimiento de los cultivos arbóreos bajo diferentes técnicas de manejo entre hileras?

29. ¿Utiliza algún tipo de fertilizante o aporte de nutrientes en sus cultivos arbóreos?

30. ¿Utiliza fertilizantes o nutrientes en sus cultivos de cobertura?

Coste

31. ¿Cómo podría superarse (subvenciones, semillas más baratas, etc.)?

32. ¿Cómo se compara el coste con el de otras prácticas de gestión como el laboreo o los herbicidas?

33. ¿Cree que más personas utilizarían los cultivos de cobertura si el coste fuera menor?

34. ¿Por qué es demasiado caro?

Would you be interested in receiving a summary of the results from this research?

21. ¿Le interesaría recibir un resumen de los resultados de esta investigación?

If possible, it would be great if the farmers could show us areas of erosion on their farm after the interview.

Appendix 3 Industry report

Effective cover crops to reduce erosion in Spanish orchards

Background

Spain is affected by severe soil erosion due to the climate and topography. Traditionally farmers have removed vegetation from between tree crops, which increases the soil's vulnerability to erosion. In a PhD project I have used plant trait analysis to find which species, that are abundant and native to Spain, are ideal for use as cover crops to control soil erosion.

In a nutshell:

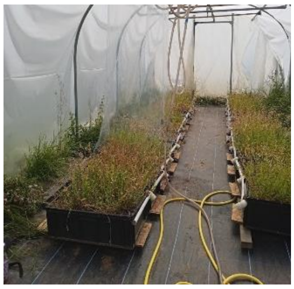
Plant cover is effective for controlling soil erosion but some species and mixes are better than others. Plant traits provide a helpful classification to identify species which may be successful. Farmers lack knowledge about effective erosion control.

Project aims:

- Analyse the above and below ground traits of native Spanish plants.
- In a field trial determine the impact of these plants on soil nutrients.
- Determine which species produce the least sediment loss, and whether a plant mix is more effective than single species.
- Interview and survey farmers to discover their opinions on cover crop use, and how it is seen culturally.

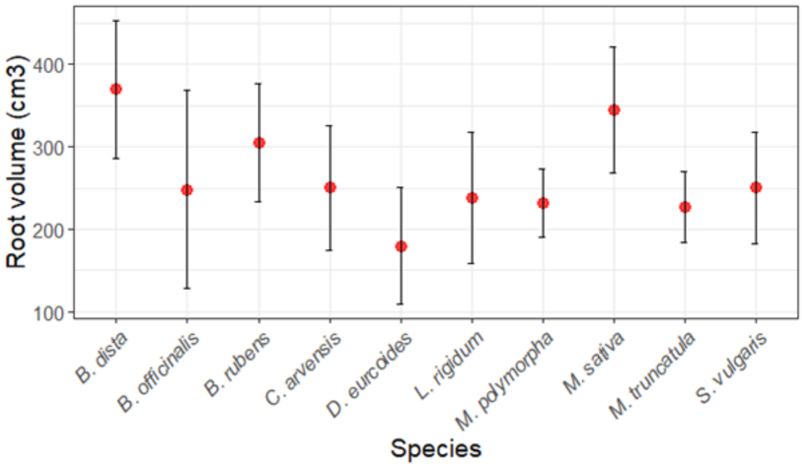
Methods

Experiments were carried out in a glasshouse, a field trial and a polytunnel. These took place at Lancaster University (UK) and in Cordoba (Spain). Farmers around Spain responded to an online survey and interviews took place in Valencia.



What are plant traits?

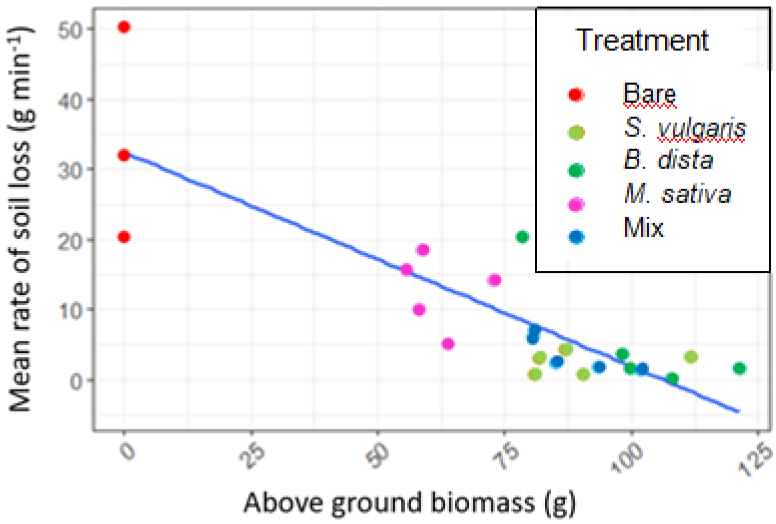
Plant traits are an alternative system to taxonomy for classifying species. Plant traits use physical attributions of plants (e.g. plant height) to group species that may not be related but could provide similar services.



Ten species were analysed for a variety of traits that prevent erosion. From these results, four species were taken to the next experiment.

The greater the root volume (left), the greater area soil which is stabilised. *B. distachyon, B. rubens, M. sativa* and *S. vulgaris* all had large root volume so were used in the next experiment.

The species (*B. dista, B. rubens, M. sativa* and *S. vulgaris*) used in the field trial had high CN ratios and high nitrogen contents, this indicates that if left on the ground as mulch they would transfer nitrogen to the soil. There was no decrease in soil nutrients where the cover crops were grown, this is likely due to the use of a nitrogen producing legume (*M. sativa*).

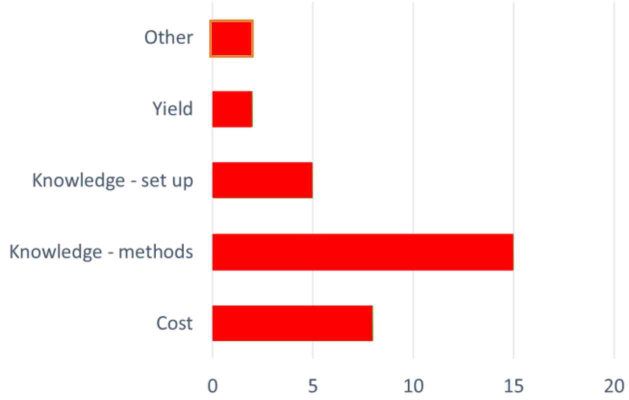


This graph shows a significant negative correlation (even if the bare plots are removed), meaning that the more plant matter on the soil surface, less soil is lost during heavy rainfall.

The mix was less effective at controlling soil erosion than expected. This is likely due to the dominance of *M. sativa* in the mix.

The results from the survey when farmers were asked what the barriers to implementing erosion control methods are shown on the right.

Lack of knowledge was the main barrier, either regarding methods of erosion control, or how to set up these methods.



Industry recommendations

- Provide farmers with unbiased information about soil erosion control methods, particularly means of identifying effective traits in spontaneous vegetation (such as soil cover).
- Support the education of agronomists in soil erosion control and the use of cover crops.
- Provide funding for farmers who incur costs when changing to a more sustainable method of controlling erosion (e.g. from herbicide use to planted cover crops).
- Encourage others in the industry to support farmers to prevent soil erosion.
- Continue funding research into soil and agricultural sustainability: no soil – no crops!

Take home message

The more ground cover provided, the less soil will be eroded. Some species are more effective than others but any ground cover will protect the soil from erosion.