# Down to Earth: Identifying and Promoting Regenerative Viticulture Practices for Soil and Human Health

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# Down to Earth:

# Identifying and Promoting Regenerative Viticulture Practices for Soil and Human Health

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A Thesis in the Field of Sustainability

for the Degree of Master of Liberal Arts in Extension Studies

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# Abstract

The objectives of this study were to quantify the yearly soil carbon sequestration of regenerative vineyard practices and explore the enablers and barriers to their adoption.

I found that soil regenerative practices can be beneficial when applied holistically and in concert with one another. There was no significant difference between the N= 345 measures of soil C sequestration I found across seven practices in viticulture but overall, animal integration (2.47 t C/ha) and non-chemical pest management (1.51 t C/ha), were highest and closest to the global average calculated in a previous study (2.05 t C/ha). Average sequestration was higher in viticulture than in annual crops, indicating a unique strength in viticulture for mitigating climate change and restoring soil and human health.

From purposefully sampling and interviewing 20 winegrowers in the canton of Vaud, Switzerland, I found that smaller vineyards were more agile in adopting regenerative practices, and winegrower land ownership increased adoption. For women, winegrower adoption depended on their knowledge and competency in a practice. Agroforestry, animal integration, and redesigning the system at the landscape level were the hardest practices to adopt. What characterized regenerative winegrowers was that they cared for soil life and were intrinsically motivated.

Using these findings, policymakers and winegrowers can take steps to overcome barriers to regenerative agriculture, and contribute to increasing healthy soils for climate mitigation, biodiversity regeneration, agricultural sustainability and human health.

# Frontispiece

*These are the vineyards in Cabasson, my family hometown in France that inspired this thesis. The vineyards share some similarities with the vineyards along Lake Geneva in Vaud, Switzerland, such as proximity to water, sloping terrain, and wild boar intrusions. Pictured: the author with her son. Picture credit: © Guillaume Dollmann*

# Author's Biographical Sketch

Jessica Villat is a French-American descendant of Charlemagne, with Corsican and Osage Indian blood, who is passionate about sustainability, nature regeneration, and people. She grew up in Provence in the south of France, home to rosé wines, in Bordeaux and in Northern California near the Napa Valley, where she had a chance to volunteer at the Schramsberg winery. Her love of people, and determination to learn from past civilizations, drove her to earn a B.A. in History from the University of California, San Diego in La Jolla, where she worked as a resident advisor. Her curiosity about people and human behavior led her to work in Japan, where in full cross-cultural immersion she began exploring co-creation, thinking systemically, and futures-thinking. After a long journey exploring strategy, people and organizational behavior working in marketing and communication, she is currently Head of Communication at the Luc Hoffmann Institute, a social innovation incubator within WWF for the nature conservation sector. She holds an M.A. in English (Teaching English to Speakers of Other Languages) from San Francisco State University and was instrumental in conceiving and establishing the nature writing-in-residence program at the Jan Michalski Foundation in Switzerland. Jessica currently lives with her partner and two children in the French-speaking part of Switzerland, surrounded by vineyards including the UNESCO World Heritage Lavaux Vineyard Terraces. In her free time, she is part of the local government, loves spending time outdoors, and puts much effort into regenerating the land she lives on. Her dream is to continue doing research and have her own farm and vineyard to manage one day.

# Dedication

I dedicate this thesis to my partner, Guillaume Dollmann, without whose unwavering patience and support, getting through this master’s program would never have been possible. I also dedicate it to my parents, who taught me that “dirt doesn’t hurt” and never doubted that I could do anything. I dedicate this study to my children, Arthur and Alexandre. Their birth inspired me to turn all my efforts towards a regenerative future and whose never-ending curiosity about Miyazaki-like spirits of the forest and interest in Narnian talking trees and animals keep the magic of nature including people alive in our home and beyond. I hope that one day when I have returned to the soil you, child or adult of another generation, will chance upon this study like I happened upon the doctoral dissertation of my great grandfather Louis Villat on Corsica. Perhaps then we will have found a way to live regeneratively so that you and all life on Earth may have a good life, full of the smell of rich, fresh soil teaming with earthworms and mycorrhizae; full of fresh, nutritious food and wine that tastes good; full of the sounds of insects, birds, and other Life on Earth; full of the feeling dirt under your fingernails and a caring community where living beings take care of one another; full of the sight of people living in harmony with the nature we are part of; and where the lullabies we sing our children to sleep with are love songs for a living soil, for other living beings, and for each other.

# Acknowledgments

I first wish to thank my research advisor Mark Leighton for offering crucial guidance at early stages of the conceptualization of this study, and nurturing my passion for ecology and regenerative agriculture. I am also deeply grateful for the thoughtful counsel of Kimberly Nicholas, my thesis director, whose reassuring guidance shaped my understanding of quantitative and qualitative methods, and whose invaluable expertise in viticulture, climate change and writing enriched my thesis. Many thanks to David Montgomery, whose books deepened my love for soil, to Niki Rust, who shares and encouraged my passion for soil sustainability and qualitative research methods, to Robert Home from FibL for his advice and inspiration on research with farmers in Switzerland, to Martin Schlaepfer for his friendship and encouragement, and to the folks at the Changins Swiss school of vini/viticulture for their time and suggestions. Thank you to French winegrowers who graciously accorded me interviews, gave me and my family vineyard tours, introduced me to the winemaking community in the Var, and even invited me to lunch in the formative stages of my research, and before COVID-19 forced me to focus on Switzerland as a geography: Jannick Utard of Malherbe in Cabasson; Yves Gros, Christelle and Jacques Rapée, and Olivier LeTartre of the Domaine les Foucques; and Olivier Tèzenas and Christophe Cottone of the Chateau de Brégançon. And last but not least, thank you to all the generous winegrower men and women in the canton of Vaud who accorded me interviews and provided the crucial primary data for this study even if they shall, for data protection reasons, not be cited here by name.

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# Chapter I

# Introduction

Soil health is the basis for all life on Earth. (European Commission. Directorate General for Research and Innovation, 2020). Healthy, living soil is the basis of many essential ecosystem services, including human health and food from agriculture. Alongside 100 climate-neutral cities, soil health is the main goal of one the European Commission's five missions, aiming to achieve a 100% increase in healthy soils by 2030. Measuring soil organic C sequestration as an indicator of soil health, and understanding the enablers and barriers for farmers to adopt regenerative practices that are focused on soil health is therefore vital.

Healthy soil is a living entity, whose wellbeing depends on its capacity to sustain and enhance plant and animal life and health, and to regenerate water and air quality health or natural ecosystem boundaries (Zehetner et al., 2015). Among its multiple critical ecosystem services and functions, soil plays a central role in climate regulation (Swiss Confederation, 2020b). Healthy soil is also vital for human health (Blum, Zechmeister-Boltenstern, & Keiblinger, 2019).

Today 60-70% of soils in Europe are unhealthy due to current management practices (European Commission. Directorate General for Research and Innovation, 2020). In Switzerland, soils of all types are in need of regeneration (Swiss Confederation, 2020b), putting in peril both their ecosystem services and functions as well as emblematic agricultural landscapes such as the eroding UNESCO World Heritage Lavaux vineyards

(Gullino, Beccaro, & Larcher, 2015). Transdisciplinary research and practical innovation that regenerates soil structure and biodiversity is urgently needed (FAO, ITPS, GSBI, CBD, & EC, 2020).

The agricultural sector is the leading driver of soil degradation (Olsson et al., 2019). The food system is responsible for a third of global anthropogenic greenhouse gas (GHG) emissions globally, with the largest contribution (71%) coming from agriculture and land use activities (Crippa et al., 2021). Agriculture must therefore be integral to climate change mitigation strategies.

For soil and human health, regenerative agriculture is a set of “farming and grazing practices that, among other benefits, reverse climate change by rebuilding soil organic matter and restoring degraded soil biodiversity” (Regeneration International, 2017, p. 1). Soil management practices have a direct impact on whether carbon and nitrogen are absorbed or emitted (ADEME, 2013), and restoring and sustainably managing soil health through sequestration of soil organic carbon (C) is central to regenerative agriculture (Rattan Lal, 2020).

Viticulture, of all cropping systems, may have more environmental, economic and cultural strength to innovate compared with other types of agriculture. For instance, the soil organic C sequestration potential for viticulture using regenerative practices could be up to four times higher than for other types of cropland (Payen et al., 2021; Zomer, Bossio, Sommer, & Verchot, 2017). Soil organic C has long been used as an indicator of soil health (FAO & ITPS, 2020).

However, to guide a shift toward soil regenerative policy and practice, research on soil regenerative practices in viticulture and the enablers for adopting them is needed.

Some studies have made qualitative rankings of regenerative soil practices in general (Oenema, Heinen, Peipei, Rietra, & Hessel, 2017), but a taxonomy of soil regeneration practices for viticulture has never, to my knowledge, been defined or quantified. Moreover, research on enablers and barriers for winegrowers to adopt regenerative practices is scarce, especially around the social factors that Newton (2020) refers to and has never been done in the French-speaking canton of Vaud on the banks of Lake Geneva, where there are close to 4000 hectares of vineyards (Canton de Vaud, 2019).

In summary, regenerative agriculture, and particularly regenerative viticulture, have the potential to sequester carbon among other benefits. However, not enough is known about the amount of carbon such practices can sequester, nor what the barriers and enablers are for farmers to adopt them in places like Switzerland, where agricultural soil is degraded.

## Research Significance and Objectives

Ideally, any study of regenerative agriculture would include both its aims: rebuilding soil organic matter through soil C sequestration and restoring biodiversity (Regeneration International, 2017). My research deals with both. The latter is significant because even though reversing biodiversity loss is central to regenerative agriculture, it is often disregarded when discussing recommended practices (Giller, Hijbeek, Andersson, & Sumberg, 2021). Moreover, transitioning to regenerative agriculture, says Gosnell (2019), “involves subjective, non-material factors associated with culture, values, ethics, identity, and emotion” (Gosnell, Gill, & Voyer, 2019).

In the first phase of this study, I define and quantify the carbon sequestration potential of soil regeneration practices. In the subsequent phases of the study, I elicited and explored social, human, natural, financial, and manufactured capital enablers for farmers to adopt regenerative practices, allowing for biodiversity issues to emerge. I focused on viticulture because it has the natural, economic and cultural strength to innovate, and on Vaud, Switzerland because winegrowing is emblematic there and soils of all types in Switzerland need regeneration. Precisely, the six phases of the study were as follows: 1) define and quantifying the soil C regenerative practices applicable to viticulture; 2) understand the effect of vineyard size in practice adoption; 3) explore the effect of vineyard ownership on adoption; 4) look at gender dynamics and adoption; 5) study which practices are the most difficult to adopt (and why); and 6) examine social factors for adoption.

In sum, the overall objectives of this research were to:

- Determine the soil regenerative practices that sequester the most carbon; and
- Explore the enablers and barriers for winegrowers in Vaud to adopt these practices.

## Background

Defining and quantifying the carbon sequestration potential of soil regeneration practices for viticulture, and contributing to understanding the enablers and barriers farmers to adopt them, contributes to a deeper understanding of regenerative practices and their enablers for policymakers and farmers that care about soil and human health.

Soil health is an imperative for human survival. As an integral part of the European Union’s missions to achieve by 2030, it contributes to the European Green Deal, Europe’s Beating Cancer Plan, and the Sustainable Development Goals (European

Commission, n.d.). This background section will proceed as follows. What healthy soil is and what its benefits are, including for human health, will be described. The subsequent part will look at the state of soil and agriculture as the leading driver of soil degradation, and how carbon sequestration can put the world back on the path to soil health. Next, regenerative agriculture will be outlined as a way to sequester soil organic C and reverse biodiversity loss to address soil degradation, and viticulture will be introduced as a strategically important crop for soil regeneration. The importance of Switzerland for soil regeneration through viticulture will be explained. Finally, known enablers and barriers to adopting regenerative practices will be outlined within the five capitals framework (Viederman, 1994), which advances important types of capital to consider besides conventional financial capital.

## Healthy Soil – Definition and Benefits Including Human Health

Healthy soil contains a wealth of microbial diversity which is not only part of our biological and genetic heritage, but is also essential for soil wellbeing and functioning (Ranjard, 2012). Healthy soil has been defined as "the capacity of soil to function as a vital living system to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health" (Kemper & Lal, 2017, p. A1). Soil is a key element of food security and climate adaptation in the face of a new and more extreme climate as our planet gets warmer (United Nations Environment Programme, 2021). It produces useful biomass in the form of medicine, food, fiber and wood, purifies drinking water, upholds infrastructure, preserves natural and cultural history, and is a bank for genetic diversity (Swiss Confederation, 2020b).

Soil is the second largest active carbon pool after the oceans, and plays a crucial role in the global carbon cycle (FAO & ITPS, 2018). Recent soil maps show that the first 30 centimeters of soil on earth contain 680 billion metric tons of carbon, more than all vegetation (which contains 560 billion metric tons of carbon) and close to twice the amount of carbon in the atmosphere (FAO & ITPS, 2018). Non-compacted soil with a healthy structure and a functioning rhizosphere can also retain more water and is therefore more resilient to drought or flooding (Swiss Confederation, 2020b).

Healthy soil is vital for human nutrition and for the human gut microbiome, for which it is a major inoculant and provides microorganisms to the gut that are essential to human health (Blum et al., 2019). The human gut microbiome and the soil rhizosphere microbiome function similarly, interact with each other and are of paramount importance to the health and performance of the people and plants they support (Blum et al., 2019). Also, most antibiotics come from soil microbes (Kemper & Lal, 2017), and symbiotic microbes and even soil pathogens appear to contribute to human immune tolerance by stimulating immunoregulatory pathways (Blum et al., 2019). Therefore, allowing biodiverse soil microorganisms to flourish stimulates what Brevic (2020) calls the "microbiome-gut-brain axis" that plays a direct role in developing and regulating the human immune system and even human behavior (Brevik et al., 2020, p. 10).

## Agriculture as a Leading Problem and Solution

However, as human civilization advances into the 21st century, soil is dangerously underestimated and often taken for granted, with research and policy that overlooks its full ecosystem service, cultural or intrinsic values (Swiss Confederation, 2020b). Today

60-70% of soils in Europe are unhealthy due to current management practices (European Commission. Directorate General for Research and Innovation, 2020). Climate change and numerous underlying socioeconomic causes, including a growing population, city expansion, and shifting diets, are contributing to the degradation of healthy living soil (FAO, 2017).

Globally, the agricultural sector is the leading driver of soil degradation (Olsson et al., 2019). Perverse incentives including certain subsidies and policies, land use changes and growing population demand for inexpensive food, drink and other products have pushed farmers toward unsustainable soil management practices (IPBES, 2018; Marchi, Ferrara, Biasi, Salvia, & Salvati, 2018). Mismanaged agriculture is not new, and has been a driver of soil erosion and the fall of civilizations for thousands of years (Montgomery, 2007). An early example in modern history is the settler land management practices that led to the Dust Bowl in the once fertile prairies of the American Midwest, literally turning soil into dust (Scholes & Scholes, 2013).

Agricultural soil makes up a significant proportion of the Earth, including in economically advanced countries. Crop and grazing lands cover more than one third of the Earth's land surface (IPBES, 2018), and in Europe, agriculture occupies 39% of land (Arrouays et al., 2015). Therefore, agriculture could play a significant role in soil regeneration. However, rapid population growth and increasing consumption are causing unprecedented pressure on soils through agricultural intensification and resulting in unsustainable soil degradation (Kopittke, Menzies, Wang, McKenna, & Lombi, 2019). Soil organic C stocks globally in agricultural soils have been found to be declining (Wiesmeier et al., 2019).

People live in an increasingly urbanized society that has decreasing contact with soil and feces, increased hygienic measures and human antibiotic use, and a diet of low fiber, processed foods (Blum et al., 2019). This way of living is linked to changes in farming practices that deplete the beneficial microbes in soil essential for ecosystem and human microbiome diversity and functioning (Blum et al., 2019). Such practices include mechanization, soil tillage, soilless cultivation (such as hydroponics), soil erosion, nutrient depletion in soil, monocultures, separation of animals from crops, excessive use of agrochemicals such as mineral fertilizers and pesticides, and use of antibiotics and hormones (Blum et al., 2019). Such practices also make agriculture the strongest driver of biodiversity loss to date (Scholes, Huang, Roué, Saw, & Mketeni, 2018). They lead to soil erosion, soil organic matter depletion, compaction, and pollution (Salomé et al., 2016). In a vicious feedback loop, the resulting ecosystem degradation has pushed farmers towards increasingly intensified chemical inputs to maintain declining productivity on exhausted soils (FAO, 2018).

Evidence abounds that success in reversing planetary tipping points could be accomplished by recognizing agricultural ecosystems as possibly the Earth’s largest biome, and of the soil, life, nitrogen and water cycles it sustains as major components of that biome (Rockström, Edenhofer, Gaertner, & DeClerck, 2020). With a shift in policy and practice, the food system could be transformed from one of the Earth’s most significant problems into the best solution for human and planetary health (Rockström et al., 2020).

## Carbon Sequestration for Soil Health

Soil organic C is the carbon that remains in soil after the decomposition of material produced by living organisms, and is the main component of soil organic matter (FAO & ITPS, 2018), which is an indicator of soil fertility (Giller et al., 2021). Soil organic C is an indicator of soil health (FAO & ITPS, 2020), but unsustainable land-management practices and land-use changes in recent decades have weakened the carbon retention of European soils (European Commission, 2011), impacting soil organic C concentrations at various soil depths (Rolando et al., 2021).

Soil C sequestration can increase the amount of available organic C in soil which in turn can positively influence the soil microbial mass (Fierer, 2017). Sequestration can be stimulated through farming practices, and recent research recommends regenerative practices such as cover crops for increasing soil organic C (Chahal, Vyn, Mayers, & Van Eerd, 2020). Some practices such as integrated crop-livestock systems can even increase soil C stock capacity (Sarto, Borges, Sarto, Rice, & Rosolem, 2020). Soil organic C and its sequestration contribute to ecosystem services such as food production and climate adaptation. However, it is extremely vulnerable to land use and soil management changes, even in deep soil layers that were previously considered resilient (Francaviglia, Di Bene, Farina, Salvati, & Vicente-Vicente, 2019).

Even if a soil regenerative practice can lead to greater C sequestration in theory, it may not always do so, for soil organic C can saturate at a certain threshold (Newton, Civita, Frankel-Goldwater, Bartel, & Johns, 2020). Therefore a practice may help sequester C when land is heavily degraded, but in soils such as intact rangelands that are already saturated with C, the practice may not be able to increase C further (Newton et al., 2020).

Measuring the impact of a farming practices on soil C sequestration can be challenging. Annual changes in soil organic C are small and highly variable throughout a landscape (Lefèvre, Rekik, Alcantara, & Wiese, 2017). Moreover, there is no universal metric for soil organic C sequestration, nor is there a standard depth at which it must be measured (Lefèvre et al., 2017). Knowledge of soil organic matter formation and stabilization is nascent, too, including the critical role that soil biodiversity plays in carbon sequestration (FAO et al., 2020). Due to spatial variability, soil organic C sampling can be expensive and there is a dearth of experimental studies to draw from (Lefèvre et al., 2017). Soil organic C responds slowly and noticeable carbon sequestration can take decades, so observed, non-simulated data on carbon sequestration in vineyards are scarce (Nistor et al., 2018).

Therefore, more and better research on the soil C sequestration of different farming management practices is needed, especially for biodiversity-intensive methods such as regenerative agriculture.

## Regenerative Agriculture

Regenerative agriculture is built on two soil health pillars: carbon sequestration and biodiversity (Giller et al., 2021). Not only is research on soil C sequestration needed, but reversing biodiversity loss also receives little attention in recommended regenerative practices (Giller et al., 2021).

Regenerative agriculture is a way to restore soil health, including C capture for climate change mitigation and biodiversity loss reversal (Giller et al., 2021). For example, regenerative practices such as minimum tillage or the use of plant cover can improve both soil C sequestration and soil biological activity (FAO et al., 2020). Agronomists frame regenerative agriculture as a mix between agroecology and sustainable intensification, and focus on the enhancement of soil organic matter and soil biodiversity (Giller et al., 2021). Regenerative agriculture goes beyond sustainability, providing systemic, exponential positive benefits versus neutralizing the status quo (Figure 1).

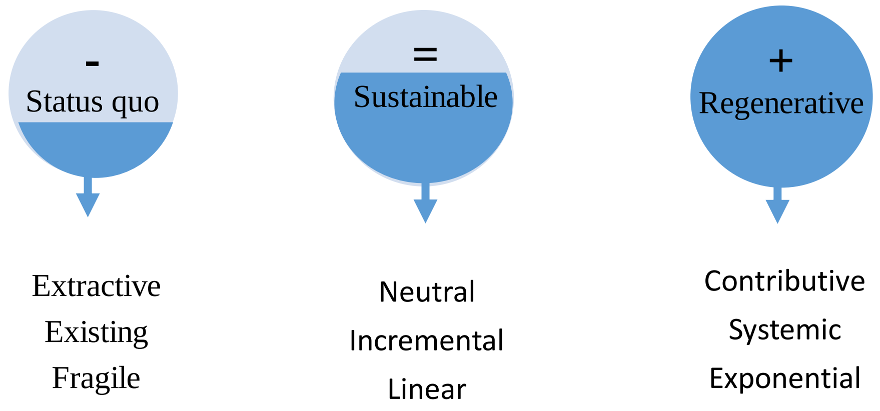


Figure 1. The regenerative approach goes beyond sustainability.

*Figure adapted from Fitzgerald (Fitzgerald, 2021).*

In its ability to sequesters soil organic C, regenerative agriculture is said to approach zero-carbon farming and some claim it could even offset greenhouse gas emissions from other sectors (Giller et al., 2021). Its biodiversity focus means that regenerative agriculture tends to be complex, knowledge-intensive, and context-specific, but essential for healthy soil life (Bélanger & Pilling, 2019).

Robert Rodale, who coined the term in the 1980s, saw regenerative agriculture as going beyond merely sustaining fundamentally dysfunctional approaches to food and fiber production (Gosnell et al., 2019). Scholars in the 1980s linked it closely to organic and ‘low external input agriculture’ (Giller et al., 2021). Regenerative agriculture has been identified with ecological, biological, and conservation agriculture, as well as with permaculture, Holistic Management, and carbon farming (Gosnell et al., 2019). To Rodale, regenerative agriculture is a holistic systems-approach to farming that regenerates the resources it uses while at the same time nourishing ecosystem, social, economic and spiritual wellbeing (Gosnell et al., 2019).

Practices usually associated with regenerative agriculture include circular farm systems and low external inputs, animal integration, avoidance of synthetic pesticides or fertilizers, reduced or no tillage, and incorporating perennials or trees. Regenerative agriculture is also associated with using compost or crop residues, using cover crops, and generally with processes that imitate complex, micro or landscape-level natural systems such as a river’s unimpeded flow (Newton et al., 2020).

By nurturing or transitioning to regenerative farming practices, much of the Earth’s topsoil can be regenerated rather than degraded (Scharmer, 2020), thereby improving both soil and human health. In its ideal form, regenerative agriculture thrives together with a regenerative culture, including ritual, foods, ceremonies, songs, stories, music and all the things that embed agriculture in a supportive and meaningful community, without which farming is socially isolated, and hard work (Soloviev & Landua, 2016).

## Viticulture

Vineyards date back to the beginning of civilization in the Mediterranean basin, and include emblematic agricultural landscapes such as the UNESCO World Heritage Lavaux vineyards (Gullino et al., 2015). A large area of land, comprising millions of hectares (7.45 Mha) is dedicated to viticulture worldwide, and vineyards make up a significant percentage of agricultural lands in Mediterranean-type climates (Payen et al., 2021; Williams, Morandé, Vaghti, Medellín-Azuara, & Viers, 2020). Moreover, viticulture may have more environmental, economic and cultural strength to innovate compared with other crops.

Environmentally, compared with annual arable crops, woody perennials such as vineyards and orchards are able to sequester significant amounts of soil organic C in their roots and in the soil through rhizodeposition, through low or no-tillage, and through the use of cover vegetation between rows (Scandellari et al., 2016). Thanks to the structural features of vines, including a complex and deep root system for direct transfer of organic carbon to subsoil, grapevines have been shown to sequester up to four times more soil organic C than other crops (Payen et al., 2021). A recent study found an average annual potential soil organic C sequestration rate for viticulture of 2.05 t C/ha/yr (Payen et al., 2021). The Payen et al. (2021) study was based on a literature search of worldwide soil organic C sequestration in experimental studies using the following vineyard carbon sequestration practices: cover crops, no-tillage, amendments, biochar application, hedging and agroforestry (Payen et al., 2021).

Conventional viticulture, as opposed to other crops, tends to be vulnerable to a wide range of pests and is highly dependent on pesticides (Muneret, Thiéry, Joubard, & Rusch, 2018). It could be that because soils are so depleted from intensive chemical pesticide use in vineyards that they have a bigger C deficit to surmount and therefore more carbon sequestration potential. Any regenerative practice is likely to have a positive impact longer-term, because under the majority of current management practices vineyards currently store very little carbon in their soil (Pellerin & Barnière, 2019).

In contrast to woody perennials, global soil organic C sequestration rates for annual arable cultures (arable, vegetable and mixed), have been found to be only 0.56 t C/ha/yr (Zomer et al., 2017). The Zomer et al. (2017) study was based on soil organic C sequestration data found for cropland in global geospatial datasets, and using current status and a 20-year modeling scenario to show the potential increase (Zomer et al., 2017). The global figure for arable crops is lower than for viticulture.

Economically, the wine industry’s higher profit margins make farmers in viticulture uniquely positioned to adopt practices that combat soil stresses (Cahill, 2009). And, grapes are a culturally important, emblematic crop whose local “gout du terroir” (taste of the earth) ties them directly to their soil of origin (Cahill, 2009, p. 6). Naturally, the choice of practice is dependent on the site-specific climatic conditions, geomorphology, socio-economic conditions, government policies, and societal factors (Oenema et al., 2017).

## Viticulture in Switzerland

Soils in Switzerland's western plateau, which houses the Vaud wine country, have the potential to be the most fertile in the world (Klaus, 2017). However, despite its vital role for people and nature, soil is Switzerland's most underestimated and neglected natural resource (Klaus, 2017). The Swiss national 2020 soil strategy admits that soil is not used sustainably, that arable land is being lost continuously, and that agricultural practices have an undeniable effect on soil (Swiss Confederation, 2020a). The effect of agricultural practices can be considerable because agriculture occupies 38% of the land surface in Switzerland (Arrouays et al., 2015). Their effects can also be considerable because they determine the sustainability of characteristically Swiss cultural landscapes. For instance, soil erosion is one of the biggest challenges that the 12th century UNESCO World Heritage Lavaux vineyards in Vaud faces (Gullino et al., 2015).

Viticulture covers 3775 hectares of land in Vaud (Swiss Wine, 2016), within which there are over 13,000 viticulture parcels (Canton de Vaud, 2019). Switzerland's Canton of Vaud wine country is divided into four main areas, which in descending size are La Côte, the Lavaux, the Chablais and Côtes de L'Orbe/Bonvillars (Figure 2). The three largest are on the banks of Lake Geneva.

The priority areas for regenerative viticulture in Vaud are La Côte, the Lavaux, and the Chablais for several reasons. For one, together they make up almost 90% of the viticulture surface in Vaud. Secondly, they all produce principally Chasselas, the signature Vaudois wine and Switzerland's most important white wine variety, whereas Côtes de L'Orbe/Bonvillars makes up a smaller viticultural surface than the others and produces other wine varieties (Canton de Vaud, 2019). Third, they have heavy, clay-limestone soils (versus maily clay soils in Côtes de L'Orbe/Bonvillars) and limestone is often linked to soil types that have nutrient deficiencies (Canton de Vaud, 2019; Point Pass Agricultural Bureau, 2016).

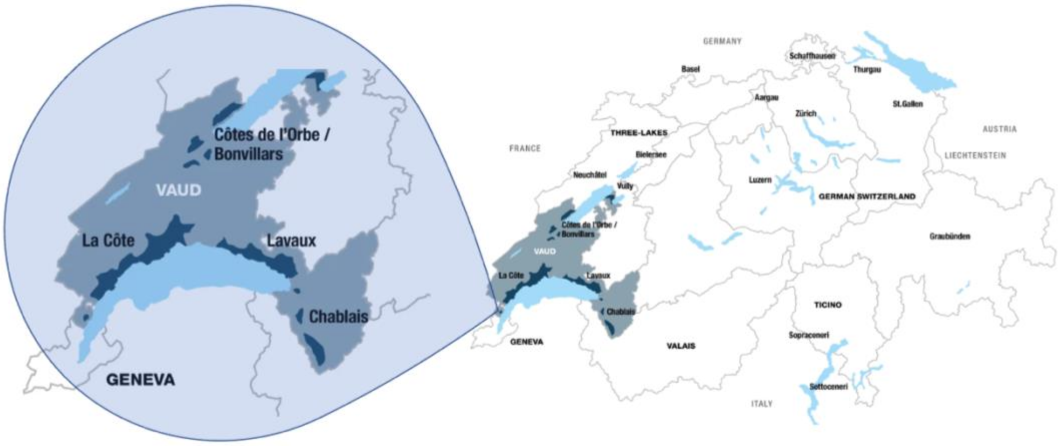


Figure 2. Map of the four wine areas in the Canton of Vaud, Switzerland.

*Map adapted from My Switzerland (Swiss Tourism Agency, n.d.)*

## The Need for Research on Barriers and Enablers (Five Capitals)

Not enough is known yet about the barriers and enablers are for winegrowers in Switzerland to adopt regenerative practices, however. Some research on enablers and barriers to adopting certain regenerative practices has been done in Germany with farmers on eight wine estates (Siepmann & Nicholas, 2018), the German-speaking part of Switzerland with 15 farmers of unspecified crops (Home, Balmer, Jahrl, Stolze, & Pfiffner, 2014), across Switzerland with 39 mostly livestock farmers (Home, Indermuehle, Tschanz, Ries, & Stolze, 2019a), and in a comparative study across Scotland and Germany with 25 livestock and cereal farmers (Burton, Kuczera, &

Schwarz, 2008). However, research on the enablers and barriers for winegrowers to adopt regenerative practices is scarce and has never been done in the French-speaking canton of Vaud, Switzerland, where there are vineyards on the banks of Lake Geneva as far as the eye can see (Canton de Vaud, 2019).

Those studies that exist of barriers and enablers point to social and human factors as determinant. Burton et al. (2008) suggests that farmers experience more than just financial losses and gains when changing their practices (Burton et al., 2008). They introduce the notion of extending ‘capital’ beyond its monetary function and considering social capital (social connections and mutual obligations) and cultural capital (Burton et al., 2008). Home et al. (2014) likewise suggests that social norms and intrinsic motivation are important in the adoption of organic practices (Home et al., 2014). Siepmann & Nicholas (2018) found that the most important motives to convert to organic farming were supportive social networks (social capital) and a pro-organic ideology (human capital) (Siepmann & Nicholas, 2018). Home et al. (2019), considered farmers as complex social networks rather than isolated actors, and found that a complex variety of external, technical, social and personal factors influenced the adoption ecological compensation areas as opposed to simply economic incentives (Home et al., 2019a). However, a recent meta-study shows that in current research, regenerative agriculture may still be understood as a practical, physical resource and centers little around social factors such as culture or spiritual wellbeing (Newton et al., 2020).

Yet according to Gosnell et al. (2019), “the process of becoming a regenerative farmer really originates in the personal sphere, and involves a commitment to ongoing experiential learning and adaptive management; explicitly identifying, and reflecting and acting on values; and linking the personal, financial, and ecological in farm and business management" (Gosnell et al., 2019, p. 11). To balance soil and environmental health, economic security, social justice, and meaningful lives, sustainable development depends on communities being able to control and use at their discretion all of the capital available to them (Viederman, 1994). Therefore, winegrower adoption of regenerative practices depends on a range of capital barriers and enablers.

A framework called the five capitals framework takes these essential types of capital for farmers into account: social, human, natural, financial, and manufactured (Viederman, 1994). Because a good understanding of these five capitals is important for exploring barriers and enablers to regenerative practice adoption, they are outlined below.

### Social Capital and its Enabling Power

Social capital plays an important role in explaining behavior and behavioral change (McNeill et al., 2018), and is linked to community and family connections, relationships and trust, culture, values, norms and shared narratives and language (Faccin, Genari, & Macke, 2017). Social enablers play a more critical role in driving soft innovations, such as regenerative viticulture practices, that require changes in skills or management (Wheeler & Marning, 2019). Whereas economies of scale are often linked with mechanization (Delord, Montaigne, & Coelho, 2015), local social networks have been found to be important for smallholder farmers, whose lifestyle- rather than production-oriented farming necessitates social relationships and community networks for simultaneous success in farming and nature conservation (Pinto-Correia, Almeida, & Gonzalez, 2017). Social capital is also an important determinant of gender equality

(Karhina, Eriksson, Ghazinour, & Ng, 2019), and among winegrowers social capital could be an enabler for women winegrowers to adopt practices. Women tend to have higher levels education and social capital, while men tend to be affected by financial capital incentives and manufactured capital advantages for men. Social enablers include information and advisory services to help winemakers adapt to complex ways of doing things rather than simply sell them technology, yet the focus at the European and national levels is not on such instruments (McNeill et al., 2018).

### Human Capital and its Enabling Power

Human capital has to do with the experience and formal or informal education levels of an individual or a social unit (Farace & Mazzotta, 2015). A winegrower’s informal education may come from working with the ‘terroir’, a concept that has been defined as “the shared intelligence of plant/soil/winegrower”, a quasi-mystical communion between the winegrower and the land (Dolan, 2019, p. 127). Human capital is positively linked with being able to obtain and exploit information (Farace & Mazzotta, 2015), and higher education levels can increase the adoption of voluntary measures (McNeill et al., 2018), such as new practices.

### Natural Capital and its Enabling Power

Natural capital can be defined as the stock and accumulation of, or a resource pertaining to, ecological features, natural resources, or ecosystem services (Henriques, 2015). There are two types of natural capital: one is renewables that regenerate on human time-scales (Helm, 2019). The other is non-renewables such as oil, gas, coal, copper, lead, and others that don’t regenerate on human time-scales and after consumption today, won’t be available for future generations (Helm, 2019). Natural capital (including land and its soil) is one of the most important capital assets for farmers and winegrowers in maintaining farm productivity (Azad & Ancev, 2020), and may therefore be important for regenerative practice adoption.

For instance, land ownership seems to matter for adoption: land tenure has been highlighted as important for adopting soil regeneration practices, with tenants more focused on short-term profit and less motivated to invest in soil regeneration or its associated practices (McNeill et al., 2018; Sklenicka et al., 2015). In Europe, many small vineyards have traditionally been managed by individual owners or families (Lieskovský et al., 2013). Ownership may matter for stewardship motivation and authoritative ability to adopt regenerative practices. Sustaining current and future wellbeing for soil and people depends on stocks of capital – including natural capital such as soil – being handed down to future generations (Solly, 2020). However, many small-scale vineyards today are being combined into large vineyards that are acquired and then owned by agricultural corporations or absentee owners (Lieskovský et al., 2013) that don’t live on the vineyard and are not in constant contact with the soil. The power of such owners may impact winegrower practices even when the original winegrower remains the tenant. Even long-term leases don’t provide the same enablers as ownership (Fraser, 2004).

Vineyard size also seems to matter: smaller farms rely less on technology and due to their heterogeneous, patchy nature, contribute more to biodiversity without sacrificing farmer autonomy or food security (Altieri & Nicholls, 2020). Also, size may matter for adoption because land is extremely fragmented in Switzerland, tending to result in small agricultural plots (Head-König, 1998) and smaller vineyards may have different enablers than large ones.

### Financial Capital and its Enabling Power

Financial capital includes cash, credit, savings and other motivational economic instruments (van den Berg, Phillips, Dicke, & Fredrix, 2020). Financial enablers are important to farmers when first adopting nature conservation practices, and especially to young farmers seeking stability (Home et al., 2014). Financial enablers have been found to drive the adoption of hard, technological innovations (such as tractors or irrigation infrastructure) (Wheeler & Marning, 2019). However, they have not been observed to be the primary driver for farmers to adopt environmental practices in Switzerland (Home et al., 2014). Even worse, financial enablers tend to undermine rather than reinforce intrinsic human enablers that drive the adoption of organic practices (Home et al., 2014; McNeill et al., 2018). Farmers are not purely motivated by economics.

### Manufactured Capital and its Enabling Power

Manufactured capital is the human capacity for artificial reproduction through, for example, machinery or infrastructure (Barinaga-Rementeria & Etxano, 2020). Infrastructure, for example, has been identified as a barrier to organic farming adoption in Switzerland, with smaller farms having lower barriers to adoption, perhaps because they have less built infrastructure to invest in changing (Home et al., 2019a). Contradictorily, Swiss farmers agree that existing infrastructure is favorable to adopting organic practices (Home et al., 2019a). However organic and regenerative are not the same, and unlike regenerative agriculture, organic practices tend to rely on machinery that can be perceived as destructive of the soil (Home et al., 2019a).

In conclusion, healthy soil is vital, including for human health. However, healthy living soil is rapidly degrading, and agriculture is the leading driver. The amount of soil organic C is an indicator of soil health and research is needed, firstly to quantify the soil C sequestration impact of regenerative practices and not less importantly to measure their impact on biodiversity. Regenerative agriculture goes beyond sustainability, and addresses both soil C sequestration and biodiversity loss reversal. Of all agricultural cropping systems, viticulture has great potential as a pioneer for regenerative agricultural practices, and the Canton of Vaud Switzerland has culturally important vineyards on some of the world's most potentially fertile soil, yet soil is neglected. In order to adopt regenerative practices, winegrowers depend on a range of capital enablers that go beyond traditional financial capital incentives. These include social, human, environmental, financial and manufactured capital.

## Research Questions, Hypotheses and Specific Aims

Therefore, my primary research questions were: How much carbon do different soil regenerative practices sequester woody perennial cropland, and how is that different from arable land? What enables or bars winegrowers in the three biggest wine areas in Vaud, Switzerland to adopt effective soil regenerative practices? I aimed through my second research question to elicit ways to address perceptions of the importance of soil health for winegrowers, including the importance of biodiversity loss reversal.

These questions were explored by testing the following hypotheses:

- H1: The most impactful soil regeneration practice for C sequestration is the use of a cover crop, both in arable and woody perennial croplands, because the practice of cover cropping is often recommended for increasing soil organic C and has been shown to positively influence soil carbon storage (Chahal et al., 2020).
- H2: For smaller vineyards, social capital is a more important enabler than manufactured capital for adopting regenerative soil practices. This is because small vineyards may not have the means to invest in machinery and infrastructure, and may instead have to rely on the power of their social networks for knowledge-sharing, shared production, shared marketing or distribution. Smaller farms may also have less infrastructure to have to change (Aldecua, Vaillant, Lafuente, & Gómez, 2017; Home, Indermuehle, Tschanz, Ries, & Stolze, 2019b).
- H3: Winegrowers that own more land adopt more regenerative practices, because farmers-landowners tend to be better stewards (Fraser, 2004; McNeill et al., 2018). Land tenure security is considered to be essential in motivating farmers to adopt sustainable land management practices, and in developed countries with a free market such as Switzerland, ownership is the form of land tenure most likely to ensure long-term investment in soil quality (Sklenicka et al., 2015).
- H4: Social and human factors matter more to women winegrowers in adopting soil regenerative practices because social relations and knowledge of regenerative land production have historically been women’s stronghold (Federici, 2009). Women have also been found to have higher levels of social capital and receive more education than men (Van Bavel, Schwartz, & Esteve, 2018).

- H5: The most difficult regenerative practices to adopt are agroforestry, animal integration and redesigning the soil system at the landscape level, because these practices require either learning a new skill that has been disassociated from winegrowing, transforming the vineyard landscape, or political maneuvering.
- H6: Social capital enablers are more important than manufactured or financial capital for winegrowers that have adopted more soil regeneration practices, because social enablers have been found to play a more critical role in driving soft innovations such as regenerative viticulture practices that require changes in skills or management (Wheeler & Marning, 2019).

## Specific Aims

To test these hypotheses the following specific aims were identified:

- For H1, use existing literature to identify and quantify the amount of carbon that nine soil regenerative practices can sequester in agriculture and viticulture.
- For H2-H6, purposefully sample a random mix of conventional, organic, and biodynamic winegrower women and men from the biggest winegrowing areas of Vaud, Switzerland to represent a spectrum of viewpoints and ascertain winegrower enablers and barriers to adopting soil regenerative practices.

# Chapter II

# Methods

In order to determine which soil regenerative farming practices have the greatest soil C sequestration potential for soil health and climate change mitigation, it was important to define the practices and ascertain the available soil organic C sequestration measurements available for them. To explore the enablers and barriers for winegrowers to adopt these practices where little research has been done, it was necessary to speak with farmers themselves. My research was therefore conducted in two phases: 1) an academic literature search to quantify the amount of C sequestration for soil regenerative practices applicable to viticulture, and 2) interviews with winegrowers to understand their social, human, natural, financial, and manufactured enablers and barriers to adopting these practices.

## Phase 1: Quantifying C Sequestration Potential for Regenerative Practices

To answer my first research question, it was important to select which soil regenerative practices to include. The criteria for selecting practices to quantify included:

- Practices relevant to viticulture (for example since grapevines are a permanent crop, crop rotations as a soil regeneration practice were discarded)
- Regenerative, closed-loop system practices (for example irrigation as a practice is generally an input external to the system as opposed to rainfed agriculture, so irrigation was discarded as not regenerative)

- Practices that have a positive impact on the environment and human health (for example increasing biodiversity and soil life, and avoiding health-impairing chemicals)
- Practices that where possible and where indicated by Oenema et al. (2017) are beneficial for crop yield, farm income, and resource efficiency (Oenema et al., 2017)

I found the following nine key regenerative practices that were finally included in the study through a literature review: agroforestry, the use of cover crops (non-legume), the use of legume cover crops, animal integration, low traffic, non-chemical fertilizer, non-chemical pest management, no tillage, and redesigning the system at the landscape level. They were gathered from the 4 per 100 initiative and the European SoilCare project (Oenema et al., 2017; Pellerin & Barnière, 2019), and all are aligned with regenerative farming definitions (LaCanne & Lundgren, 2018).

Table 1 includes a definition and the source of each of these nine practices. For a longer description of each practice including its benefits, see Appendix 1.

## Does Applying a Cover Crop Sequester the Most Carbon? (H1)

To quantify these nine regenerative practices and address my fist hypothesis that a cover crop sequesters the most carbon, I ran two Google Scholar queries in October 2020 to find studies that measured soil C sequestration for each practice. In the first query, I used the following search terms: ("vineyard" OR "viticulture" OR "wine" OR "grape*" OR "permanent crop") AND (“management practice” OR “cropping system") AND ("carbon sequestration" OR "soil organic carbon") AND ("Kg C”). For the second

Table 1. Nine regenerative practices relevant for viticulture defined.

| **Practice** | **Definition and definition source** | **Regenerative practice source** |
|---|---|---|
| Agroforestry | Integrating trees (and bushes) within and around an agricultural field. | (1); (2); (3) |
| Cover crop (non-legume) | Having vegetation in vineyard alleys (and under the vines) (Scandellari et al., 2016) | (1); (2); (3) |
| Cover crop (legume) | Using a nitrogen-fixing-cover crop in vineyard alleys or under vines instead of high nitrogen fertilizer inputs (Pisciotta et al., 2021) | (1); (3) |
| Animal integration | Combining crop and animal systems to reduce the negative externalities of cropland being separate from animal feeding operations | (1); (3) |
| Low traffic | Reducing heavy traffic loads and farm machinery (Giraldez Cervera, Oleson, & Schoeder, 2017) | (1); (3) |
| Non-chemical fertilizer | Eliminating chemical/synthetic inputs and using organic fertilizers instead (Gosnell et al., 2019), (Larbodière et al., 2020) | (1); (3) |
| Non-chemical pest management | Eliminating chemical inputs such as herbicides and pesticides to preserve the biological system of soil life (Gosnell et al., 2019) | (1); (3) |
| No-tillage | Completely eliminating soil ploughing in agricultural systems (Beach, Laing, Walle, & Martin, 2018) | (1); (3) |
| Redesigning the system at the landscape level | Viewing the landscape and the vineyard within it as an ecosystemic continuum (Beach et al., 2018) | (1); (3) |

*(1) (Oenema et al., 2017);(2) (Pellerin & Barnière, 2019);(3) (LaCanne & Lundgren, 2018)*

query, I used the following terms: ("vitis vinifera") AND (“practice” OR “manage*") AND ("soil organic carbon") AND ("Switzerland"). I then sorted the studies and added further reference papers.

Based on the article title and abstract, I sorted studies into likely relevant and not relevant to measuring one of the nine soil regenerative practices. Likely studies were scanned to determine if they actually included a C sequestration measure for one of the defined management practices, and excluded if not. Where relevant and possible, I also expanded the data from meta studies or added studies that were referenced. For example, I added 209 additional studies with C sequestration figures for non-chemical fertilizer from a meta study on organic farming (Gattinger et al., 2019). Additional sources recommended by entities such as the Changins School of Viticulture and Oenology, the Swiss Research Institute of Organic Agriculture (FiBL), or the University of Geneva’s Institute for Environmental Sciences were also included.

For each relevant study, I noted the following information: document identifier (DOI), the author and year, the title of the study, the depth of the soil sample, the length of the study in years, and which of the nine soil regenerative practices the study referred to. I also marked the kind of land use per study, putting viticulture and orchards in the same category because recent research indicates that the specific threats to a vineyard soil can be assessed in the same way as any orchard ecosystem organized in rows and alleys (Diti et al., 2020). The carbon sequestration rate was also noted and converted to per hectare per year (t C/ha/yr) for the results to be comparable. Some potential studies did not have a soil organic C sequestration figure, did not have a baseline figure to extract a rate over time, or the causal effect of the practice could not be dissociated from other practices. These were eliminated. For some studies, a practice was found that could be used as a proxy. For example, there were hardly any studies on animal integration, but manure application (a byproduct of animal integration) could be used as a proxy.

Many of the studies found were of soil regenerative practices applied to other types of agricultural land uses than viticulture. It might be tempting to assume that the effect of regenerative practices on soil would be the same regardless of the agricultural land use, but I wanted to make sure. Therefore, I divided the sample studies into two land use groups: arable (including arable, vegetable and mixed land) and woody perennial (including viticulture and orchards). These groups correspond to categories used in other studies (Gattinger et al., 2019).

Each soil organic C sequestration figure represented a data point for one of the practices. I then used those data samples to draw two box plots comparing the sequestration rates of different practices. The first box plot examined the effect of the practices on soil in arable croplands, and the second plot examined the effect on woody perennials. I then ran an ANOVA and graphed the average of each practice for the two land uses, followed by t-tests to compare means within practices (Table 2).

Table 2. Hypothesis 1: methodologies and analysis methods used.

| Hypothesis | Methodology | Analysis method |
|---|---|---|
| Hypothesis 1:<br>Applying a *cover crop* sequesters the most carbon, both in arable and woody perennial land uses. | Literature meta-analysis (n = number of practice-specific soil C sequestration measures found in studies) | Box plot<br>X= practices (categorical)<br>Y= carbon sequestration rate (Mg C ha-1 year-1)<br>ANOVA<br>(significance level = 0.1)<br>Paired t-tests to compare woody perennial and arable within practices |

## Phase 2: Understanding Winegrower Enablers and Barriers

To test H2-H6, I conducted interviews with 20 winegrowers in Vaud. Before undertaking research involving human subjects, I obtained approval from the Institutional Review Board (IRB) to carry out the study. It was also important to select the most relevant and diverse sample of Swiss Vaudois winegrowers to interview and elicit enablers and barriers from. In qualitative research, a small number of samples can provide in-depth inquiry into a topic, and saturation – the point where all relevant themes have been raised – can happen after 12 interviews (Home et al., 2014). Since 12 to 20 participants are recommended in interview studies (Sim et al., 2018), I purposefully sampled 20 winegrowers. Having 20 samples also allowed me to be able to do further quantitative analysis, which usually requires a larger number of samples than qualitative studies. Winegrowers were selected to include a balance of men and women, a geographic spread across the three biggest winegrowing areas of the canton of Vaud so that I would have enough samples from each to potentially compare areas, and a diversity of conventional, organic, and biodynamic winegrowers (Table 3).

The interviews were conducted in French, the official language of the Canton of Vaud. For the first part of the interview, I used a set of open and closed questions to inform my hypothesis-testing, including winegrower gender, vineyard ownership and size, and practices already adopted. I also asked about certification and the main soil threats to the vineyard (see questions used for the winegrower interviews, Appendix 2).

Table 3. Snapshot of winegrowers interviewed by vineyard size.

| Sample number | Region | Gender | Vineyard size (ha) | Self-ownership | Other owner | Certification |
|---|---|---|---|---|---|---|
| W11 | La Côte | Man | 0.43 | 35% | Landlord(s) | Conventional |
| W12 | La Côte | Man | 1 | 0% | Parent(s) and Landlord(s) | Conventional |
| W13 | Chablais | Woman | 2.7 | 100% | None | Biodynamic |
| W16 | Lavaux | Woman | 3 | 0% | Parent(s) and Landlord(s) | Conventional |
| W1 | Lavaux | Woman | 4 | 25% | Landlord(s) | Conventional |
| W2 | Lavaux | Man | 5 | 100% | None | Organic |
| W5 | Chablais | Man | 8 | 0% | Partner(s) | Conventional |
| W6 | La Côte | Man | 8.5 | 0% | Landlord(s) | Conventional |
| W7 | La Côte | Woman | 10 | 10% | Parent(s) | Organic |
| W10 | La Côte | Man | 10 | 45% | Partner(s) | Conventional |
| W14 | La Côte | Man | 10.5 | 20% | Sibling(s) | Conventional |
| W15 | Lavaux | Woman | 12 | 0% | Parent(s),<br>Landlord(s) | Conventional |
| W17 | Chablais | Man | 12.5 | 0% | Parent(s) | Conventional |
| W18 | La Côte | Woman | 13.5 | 75% | Parent(s) | Biodynamic |
| W19 | Chablais | Man | 16 | 0% | Landlord(s) | Conventional |
| W20 | La Côte | Woman | 17 | 6% | Sibling(s) | Conventional |
| W3 | La Côte | Man | 20 | 100% | None | Conventional |
| W4 | La Côte | Man | 23 | 83% | Landlord(s) | Biodynamic |
| W8 | La Côte | Man | 25 | 50% | Sibling(s) | Organic |
| W9 | La Côte | Woman | 32 | 0% | Parent(s),<br>Landlord(s)<br>Partner(s) | Biodynamic |

*The sample number refers to the winegrower sample.*

To gather the remaining data on enablers and barriers, I used an interview methodology based on personal construct theory, called the ‘Repertory Grid Technique’ (see Repertory Grid used for the interviews, Appendix 3). Personal construct psychology was developed in the clinical field, but can and has been applied to a wide number of areas (Zeigler-Hill & Shackelford, 2020). The Repertory Grid method, which mentally maps and identifies what people think about an issue (Jankovic, 2003), allowed me to explore the psychological reasons behind why winegrowers do or don’t adopt certain practices, and to elicit social, human, environmental, financial, and manufactured capital enablers/barriers. Although the easier method of direct questioning is often used to investigate motivational enablers and barriers, it may be difficult for interviewees to articulate their views on complex socio-ecological topics (Goffin, 2002). The Repertory Grid method, however, elicits detailed descriptions of complex topics (Jankowicz, 2004). Moreover, it is less contaminated by the researcher’s mental framing (Jankowicz, 2004). In personal construct theory, the researcher has to be willing to see the world through the eyes of the research subject, which is key for studying motivation.

Within personal construct theory, every person is considered a scientist, and makes hypotheses by applying bipolar personal constructs (such as “good-evil”) to elements of the world (such as people, events, or agricultural practices) (Zeigler-Hill & Shackelford, 2020). The administration of the Repertory Grid technique unfolded as follows. In order to examine the psychological enablers and barriers to adoption of soil regenerative practices, I provided the nine regenerative practices listed in Table 1 as elements to each winegrower interviewed. Those elements were then used to elicit approximately ten paired constructs from winegrowers by asking them to describe how elements (practices) were different from others in terms of what enabled or barred their adoption. The first nine or so paired constructs were elicited (supplied by participants). A tenth paired construct on general ease of adoption was imposed for my own hypothesis-testing.

To elicit each paired construct, I showed the winegrower three random elements (regenerative practices) and asked him/her to explain how two of the practices are different from the third in terms of what has enabled or barred them from adopting it. To ensure that the construct could be conceived broadly and using the winegrower's own words, I advised the winegrower that the construct could be any kind of enabler or barrier, be it social, financial, human, environmental or manufactured. I then wrote down their response and displayed the construct to them as it was elicited.

After eliciting each construct, I asked the winegrower to rate each element. The constructs indicate how the winegrower thinks, and the ratings indicate what they think (Jankovic, 2003). The ratings were always on a 5-point scale, with '1' being closest to the emergent pole of the construct (e.g. "My other winemaker friends are doing it") and '5' being closest to the implicit pole of the construct (e.g. "My other winemaker friends are not doing it"). Each construct in a repertory grid has a polarity; in this study one pole corresponding to an enabler and the opposite pole corresponding to a barrier to practice adoption. For example, a winegrower might note that the practice of cover cropping is closest to "My other winemaker friends are doing it", and rate it therefore a '1'. The elements, constructs, and ratings combine to illustrate the winegrower's meaning, which in this example case might be that because the winegrower's friends are doing it, the practice of applying a *cover crop* is easier to adopt (See example, Figure 3). Each interview lasted between one and two hours.

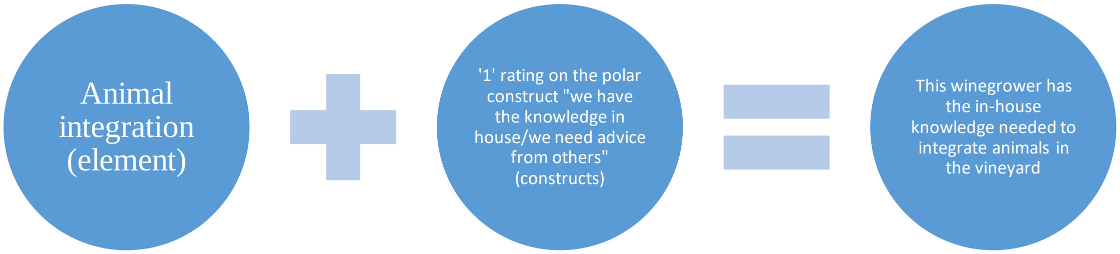


Figure 3. How elements, constructs and ratings combine to mean something.

*Note: for the paired construct in this illustration, a '1' rating would mean that the winegrower was positioned closest to "we have the knowledge in house" and a '5' rating meant they positioned themselves closest to "we need advice from others".*

I then did a categorical analysis of the 10 or so constructs per winegrower in NVivo (*NVivo*, 2020). Each construct was categorized as pertaining to social, human, natural, financial or manufactured capital and the subcategories of each capital. Using this categorization system, it was possible to compare individual constructs across grids to determine how winegrowers think about enablers and barriers.

The Repertory Grid is a powerful integrative tool that allows bridging between qualitative and quantitative research techniques and disciplines to test hypotheses

(Jankowicz, 2004) in the socio-ecological space that this study sits in. The ratings for each construct not only provided information on what the winegrowers thought about the practices (versus the constructs, which provided the how), but also provided quantitative data for statistical testing. It therefore was a singular way to test my remaining hypotheses. The significance level for all statistical tests (H2-H6) was set at $p<0.10$ or 10%.

### Does Social Capital Matter More for Smaller Vineyards? (H2)

My second hypothesis (H2), was that social capital mattered more than manufactured capital to smaller vineyards because smaller vineyards may rely more on social networks than on expensive machinery and infrastructure to get things done. However, since size is subjective, I had to determine the threshold between 'smaller vineyards' and a 'larger vineyards'. For example, the average vineyard size in California is 33 hectares (Alston, Lapsley, & Sambucci, 2018). However, for an independent winemaker in Switzerland, 4.2 hectares is the average size (Association Suisse des Vignerons-Encaveurs Indépendants, n.d.). Taking this average as the threshold, vineyards with less than 4.2 hectares were considered small and vineyards with 4.2 hectares or more were considered large (Figure 4). I considered using the sample average rather than Swiss average, since most of the study samples (75%) fell into the 'large' category and the sample average is more than two times larger than the Swiss average, but the study distribution does not seem to be representative of the split between small and large winegrowers in Switzerland. Part of the reason why this split is not representative is that at the time of recruitment I did not have information on the size of the winegrowers' vineyards as this was an interview question. For background research, only rarely was the size of the vineyard stated publicly its website or elsewhere.

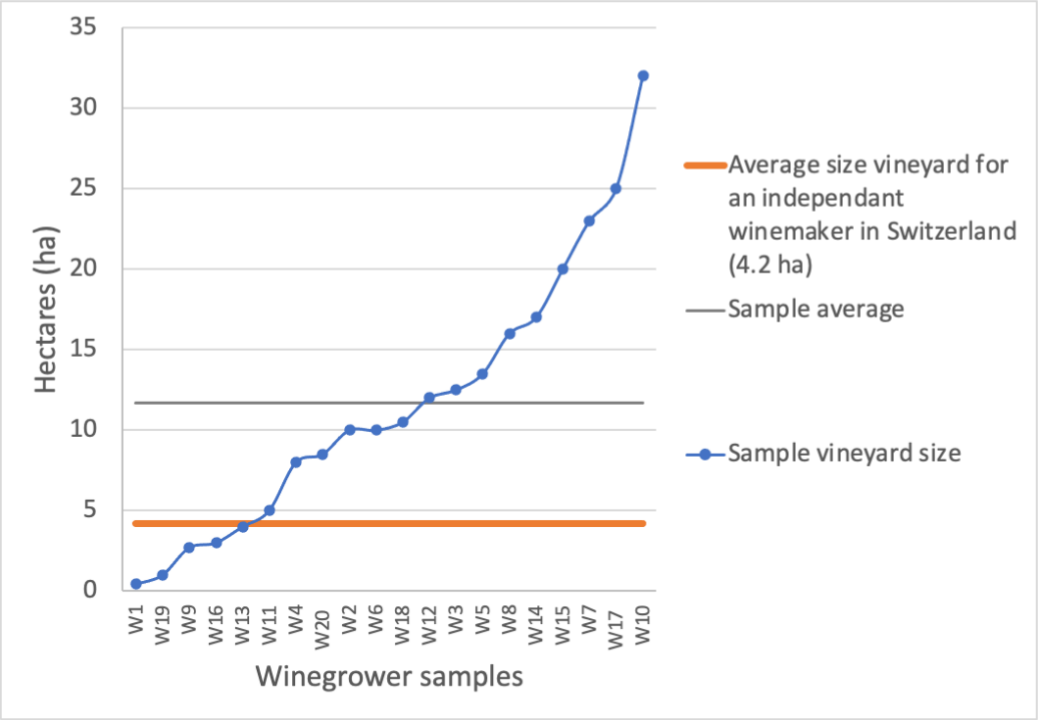


Figure 4. Vineyard sizes and threshold between ‘small’ and ‘large’ vineyards.

*The chosen threshold of 4.2 hectares for the cutoff between "small" and "big" vineyards is the average vineyard size of an independent winemaker in Switzerland.*

From my content analysis of the constructs in the repertory grids, I counted the number of constructs per type of capital and by vineyard size for all winegrowers. This count allowed me to determine whether social capital was mentioned more than manufactured capital by smaller winegrowers in comparison to larger winegrowers. I then ran a chi-square analysis of the count results (Table 4) to test whether smaller vineyards found social capital to be more important than manufactured capital for adopting regenerative soil practices.

Table 4. Hypothesis 2: methodologies and analysis methods used.

<table>
<tr><th>Hypothesis</th><th>Methodology</th><th>Analysis method</th></tr>
<tr>
<td>As compared with larger winegrowers (over 4.2 hectares), smaller winegrowers will find social capital more important than manufactured capital for adopting regenerative soil practices.</td>
<td>Questions asked:<br>-What is the size (in hectares) of the vineyard?<br>-Barriers and enablers elicited from Repertory Grid interview<br><br>N = number of constructs</td>
<td>Content analysis of Repertory Grids to determine whether number of answers are categorized by manufactured, natural, human, social, or financial capital.<br><br>Chi-square analysis:<br>X= vineyard size (hectares)<br>Y= number of constructs related to social, manufactured, or other capital enablers
<table>
<tr><td></td><td colspan="5">Number of constructs per capital type</td></tr>
<tr><td></td><td>Fin.</td><td>Hum.</td><td>Manuf.</td><td>Nat.</td><td>Soc.</td></tr>
<tr><td>Smaller Vineyard (< 4.2 hectares)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Bigger Vineyard (>= 4.2 hectares)</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>
</td>
</tr>
</table>

### Does Ownership Matter for Regenerative Practice Adoption? (H3)

My third hypothesis (H3) was that winegrowers with higher percentage ownership of land parcels would adopt more soil regenerative practices, because studies show that farmers who own their land steward it to maximize soil conservation (Fraser, 2004). To begin, I took vineyard size and hectares owned to generate an ownership percentage for each winegrower. To test whether vineyard ownership at all (>0% ownership) has an impact on soil regenerative practice adoption, I ran a chi square test to examine the relation between vineyard ownership and the number of soil regenerative practices adopted per winegrower (Table 5).

Table 5. Hypothesis 3: methodologies and analysis methods used.

<table>
<tr><th>Hypothesis</th><th>Methodology</th><th>Analysis method</th></tr>
<tr>
<td>Winegrowers that own a greater percentage of land adopt more regenerative practices, because farmers that own their own land tend to be better stewards.</td>
<td>Questions asked:<br>-Which of the following soil regeneration management practices do you already practice? (checklist)<br>-Who owns the vineyard?<br><br>N = number of winegrowers interviewed</td>
<td>Chi-square analysis:<br>X= percentage ownership (categorical)<br>Y= # of practices adopted (categorical)
<table>
<tr><th></th><th>Non-regenerative</th><th>Regenerative</th></tr>
<tr><td>Non-controlling ownership</td><td></td><td></td></tr>
<tr><td>Controlling ownership</td><td></td><td></td></tr>
</table>
Cross-tab analysis 1: number of coding references per capital type in each quadrant above, and content analysis of underlying constructs. Cross-tab analysis 2: number of winegrowers in each quadrant with landlord involvement.
<table>
<tr><th></th><th>Smaller # of practices adopted</th><th>Greater # of practices adopted</th></tr>
<tr><td>Ownership type 1</td><td></td><td></td></tr>
<tr><td>Ownership type 2</td><td></td><td></td></tr>
</table>
</td>
</tr>
</table>

However, sufficient ownership for winegrowers to be able to decide on regenerative practices is key. In principle in Switzerland, co-owners in an agricultural property can exploit all parcels of land, within the limits of compatibility with other co-owners (Convers, 2005). Yet usage rights are according to local usage customs, and rules must be set independently to ensure harmonious cooperation (Convers, 2005), so ensuring enough ownership for control over decision-making is important. I therefore also ran a chi-square test to see if a certain percentage ownership has an impact on soil regenerative practice adoption. The threshold for ‘controlling owners’ was set at 50% or more, because especially in primarily family-run businesses like winegrowing in Switzerland, ownership is *the* way to influence the family. I set therefore set ‘non-controlling owners’ as those owning less than 50% of the vineyard, for although it is possible to own a firm in Switzerland without controlling it, 50% ownership is required for control (Frey, Halter, Zellweger, & Klein, 2004).

The threshold between smaller and greater number of practices adopted was set at the average number of practices adopted (4.35), which fell just below the biodynamic winegrower having adopted the least number of practices. Those having adopted 4.35 practices or more were considered ‘regenerative winegrowers’ and the rest, ‘non-regenerative’. As Figure 5 indicates, conventional, organic or biodynamic winegrowers could all be considered regenerative, because my definition of regenerative depended not on a label but on the number of soil regeneration practices adopted.

The chi-square test answered whether ownership was related to being regenerative, but it didn’t tell me how. Therefore, I used a crosstab query in NVivo to visualize the capital types most mentioned by the winegrowers in each of the chi-square quadrants from my second chi-square analysis looking at controlling versus non-controlling owners. This allowed me to see for example what capital types enablers are important to a regenerative, controlling owner and to examine the underlying constructs within each capital type to understand how they think.

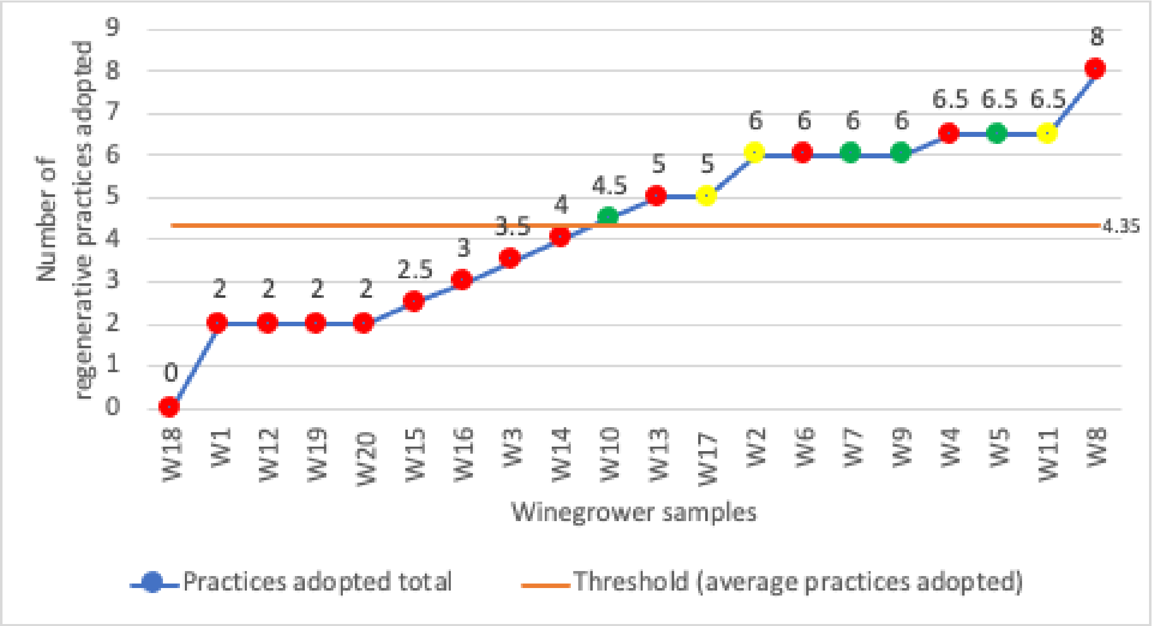


Figure 5. Threshold between regenerative and non-regenerative winegrowers.

*Note: Winegrower certification is indicated by the color of the dots. The color key for the winegrower samples is as follows: red dots = conventional, yellow dots = organic, and green dots = biodynamic.*

Finally, I also had data on the type of vineyard ownership, so I conducted a separate cross-tab analysis in NVivo to see if the type of vineyard ownership found in the controlling or non-controlling ownership chi-square quadrants might play a role in practice adoption.

## Are Social and Human Capital More Important for Women? (H4)

My fourth hypothesis was that social and human factors matter more for women winegrowers. This is based on academic research that indicates that communal and social relations, as well as female intellect and knowledge of regenerative land reproduction were the foundations of female power in the centuries preceding the rise of capitalism and industrialism in Europe and in Switzerland (Federici, 2009). Some examples include midwives helping women control births, thereby safeguarding population sustainability in order not to exhaust soil, or women's role in peasant community agriculture, festivals, songs, games and feasts on the commons before the enclosures and land privatization (Federici, 2009). However, women's social and human capital was repressed through two centuries of witch hunting starting in the 16th century, including in Switzerland where in the early phases of the witch hunt in Switzerland witches were called "Waudois" (the women of Vaud or of the forest) (Federici, 2009). This social and human capital repression is important to bear in mind as women's involvement in agriculture strengthens in Vaud and elsewhere to regenerate soil sustainably after four centuries of capitalism and industrialism. And while going back 400 years may seem excessive to some, gender issues are known to be not only relational but also situated culturally and historically (Pecis, 2016).

To test this fourth hypothesis, I assigned a capital category to each construct for each winegrower in NVivo. I then tabulated the number of constructs per capital category for men and for women. I then performed a chi-square test of independence to see whether men or women evoked more constructs in one category or another (See methods, Table 6).

To see the reasons for the differences in capital evoked, I compared the chi square quadrant with the largest count differences between men and women. I had interviewed eight women and twelve men winegrowers. Because the sample sizes were unequal (there were 33% more men than women), I calibrated the construct counts so that they could be compared. The absolute construct counts for men were reduced by 33% and rounded to the nearest integer.

Finally, to show how human capital might differ between men and women, I ran a word cloud analysis of the underlying constructs for the capitals with the largest calibrated count difference between men and women. The word cloud generator was applied to the full constructs elicited from the winegrowers (as opposed to just the capital categories that I inferred from those constructs).

Table 6. Hypothesis 4: methodologies and analysis methods used.

<table>
<tr><th>Hypothesis</th><th>Methodology</th><th>Analysis method</th></tr>
<tr>
<td>Social and human factors matter to women winegrowers in adopting soil regenerative practices</td>
<td>Questions asked:<br>-Do you identify yourself as a man, a woman, or other?<br>-Barriers and enablers elicited via Repertory Grid.<br><br>N = number of constructs</td>
<td>Content analysis to tag constructs by capital category<br>Chi square analysis:<br>X= gender (categorical)<br>Y= number of constructs elicited per type of capital (categorical)
<table>
<tr><td></td><td colspan="3">Number of constructs per capital type</td></tr>
<tr><td></td><td>Financial</td><td>Social</td><td>Etc.</td></tr>
<tr><td>Men</td><td></td><td></td><td></td></tr>
<tr><td>Women</td><td></td><td></td><td></td></tr>
</table>
Word cloud analysis of the underlying constructs in the chi square quadrants.</td>
</tr>
</table>

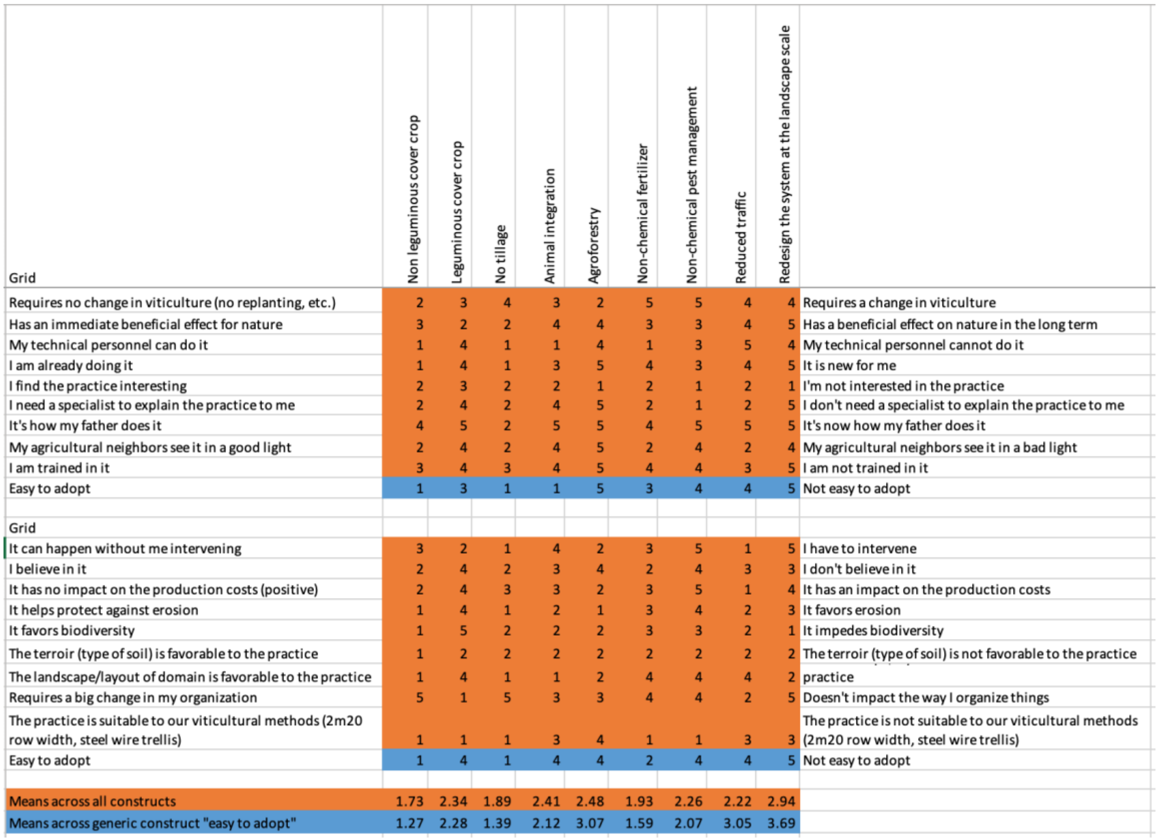
## Which Regenerative Practices are the Hardest to Adopt? (H5)

Meanwhile, my fifth hunch was that agroforestry, animal integration and redesigning the soil system at the landscape level are the most difficult practices for winegrowers to adopt, for they require either transformation of the vineyard landscape, learning a new skill that has been disassociated from winegrowing, or political maneuvering. The repertory grid method is more complex than other tests and questionnaires, thereby allowing structured data for this hypothesis to be collected. This complexity requires equally complex methods of analysis (Faccio, 2012), which I was able to exploit in testing this hypothesis (Table 7).

Table 7. Hypothesis 5: methodologies and analysis methods.

| Hypothesis | Methodology | Analysis method |
|---|---|---|
| *Agroforestry, animal integration* and redesigning the soil system at the landscape level will be the hardest practices to adopt, for they require either political maneuvering, transformation of the vineyard landscape, or learning a new skill that has been disassociated from winegrowing. | Questions asked:<br>-Barrier and enablers per winegrower elicited using the Repertory Grid interview technique.<br>N = number of constructs | Analysis:<br>Likert-type Scale analysis (Harpe, 2015), taking the arithmetic mean for each element across all samples for the given construct “easy to adopt”, “not easy to adopt”, and the mean across all remaining constructs for verification.<br>Content analysis and Principal Components analysis to look at the relationship between elements. |

To indicate which practices were easier to adopt in general, I created a composite grid by combining all 20 winegrower grids together. Each paired construct represented an enabler and a barrier, and a person can always construe the same thing differently on separate occasions (Jankowicz, 2004), so the given “Easy to adopt”/ “Not easy to adopt” construct provided a first way to measure ease of adoption, while the remaining constructs provided a proxy, verification measure for ease of adoption. I organized each repertory grid such that the enabler (ease of adoption) constructs were always on the left-hand side, reversing the constructs and the ratings if not. Figure 6 shows two sample grids in the composite grid, with the generic “easy to adopt construct”, all other constructs, and their means across all grids.



| Grid | Non leguminous cover crop | Leguminous cover crop | No tillage | Animal integration | Agroforestry | Non-chemical fertilizer | Non-chemical pest management | Reduced traffic | Redesign the system at the landscape scale | |
|---|---|---|---|---|---|---|---|---|---|---|
| Requires no change in viticulture (no replanting, etc.) | 2 | 3 | 4 | 3 | 2 | 5 | 5 | 4 | 4 | Requires a change in viticulture |
| Has an immediate beneficial effect for nature | 3 | 2 | 2 | 4 | 4 | 3 | 3 | 4 | 5 | Has a beneficial effect on nature in the long term |
| My technical personnel can do it | 1 | 4 | 1 | 1 | 4 | 1 | 3 | 5 | 4 | My technical personnel cannot do it |
| I am already doing it | 1 | 4 | 1 | 3 | 5 | 4 | 3 | 4 | 5 | It is new for me |
| I find the practice interesting | 2 | 3 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | I'm not interested in the practice |
| I need a specialist to explain the practice to me | 2 | 4 | 2 | 4 | 5 | 2 | 1 | 2 | 5 | I don't need a specialist to explain the practice to me |
| It's how my father does it | 4 | 5 | 2 | 5 | 5 | 4 | 5 | 5 | 5 | It's now how my father does it |
| My agricultural neighbors see it in a good light | 2 | 4 | 2 | 4 | 5 | 2 | 4 | 2 | 4 | My agricultural neighbors see it in a bad light |
| I am trained in it | 3 | 4 | 3 | 4 | 5 | 4 | 4 | 3 | 5 | I am not trained in it |
| Easy to adopt | 1 | 3 | 1 | 1 | 5 | 3 | 4 | 4 | 5 | Not easy to adopt |
| | | | | | | | | | | |
| Grid | | | | | | | | | | |
| It can happen without me intervening | 3 | 2 | 1 | 4 | 2 | 3 | 5 | 1 | 5 | I have to intervene |
| I believe in it | 2 | 4 | 2 | 3 | 4 | 2 | 4 | 3 | 3 | I don't believe in it |
| It has no impact on the production costs (positive) | 2 | 4 | 3 | 3 | 2 | 3 | 5 | 1 | 4 | It has an impact on the production costs |
| It helps protect against erosion | 1 | 4 | 1 | 2 | 1 | 3 | 4 | 2 | 3 | It favors erosion |
| It favors biodiversity | 1 | 5 | 2 | 2 | 2 | 3 | 3 | 2 | 1 | It impedes biodiversity |
| The terroir (type of soil) is favorable to the practice | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | The terroir (type of soil) is not favorable to the practice |
| The landscape/layout of domain is favorable to the practice | 1 | 4 | 1 | 1 | 2 | 4 | 4 | 4 | 2 | practice |
| Requires a big change in my organization | 5 | 1 | 5 | 3 | 3 | 4 | 4 | 2 | 5 | Doesn't impact the way I organize things |
| The practice is suitable to our viticultural methods (2m20 row width, steel wire trellis) | 1 | 1 | 1 | 3 | 4 | 1 | 1 | 3 | 3 | The practice is not suitable to our viticultural methods (2m20 row width, steel wire trellis) |
| Easy to adopt | 1 | 4 | 1 | 4 | 4 | 2 | 4 | 4 | 5 | Not easy to adopt |
| | | | | | | | | | | |
| Means across all constructs | 1.73 | 2.34 | 1.89 | 2.41 | 2.48 | 1.93 | 2.26 | 2.22 | 2.94 | |
| Means across generic construct "easy to adopt" | 1.27 | 2.28 | 1.39 | 2.12 | 3.07 | 1.59 | 2.07 | 3.05 | 3.69 | |

Figure 6. Sample composite grid with “easy to adopt construct” and means.

*The numbers, ranging from one to five, are the ratings I elicited from the winegrowers during the interviews. At the bottom are the means of the respective ratings. The color orange corresponds to the elicited constructs and the mean rating across all these constructs (calculated vertically). The color blue corresponds to the generic “easy to adopt/not easy to adopt” construct provided to each winegrower and the mean rating across this one construct (calculated vertically). The colors correspond to those in Figure 16.*

For example, take animal integration in Figure 6: animal integration received a mean rating of 2.12 across the generic ease of adaption construct, indicating that it is closer across all winegrowers to ‘easy to adopt’ on the ‘1’ end of the rating scale than to ‘not easy to adopt’ on the ‘5’ end of the rating scale. Similarly, animal integration received a mean rating of 2.41 across all other constructs, indicating that animal integration is closer to the enabling end of the scale and therefore on average falls on the easy-to-adopt side.

To better understand the reasoning behind the practices with the highest mean ratings in terms of difficulty of adoption, I then performed a principal component analysis. A principal component analysis shows the relationship between elements: the distance between two elements reflects the ratings each element received on all constructs, and any elements that are close together in a principal component graph will have received similar ratings across constructs, and may be construed in a similar fashion (Jankowicz, 2004). In such a principal components analysis, the composite repertory grids elicited from winegrowers are treated as a geometric configuration in which the constructs form the axes of an n-dimensional space and the elements are positioned according to their ratings on the constructs (Gaines & Shaw, 2018). In order to perform a principal component analysis, I used the construct content analysis from my testing of hypothesis four to assign each construct to a category of capital and then, for precision, a subcategory thereof. I retained for each subcategory a paraphrase of the constructs related to the subcategory. Figure 7 shows what the building blocks could look like of a principal component analysis generated with the Rep Plus software (Shaw & Gaines, 2018).

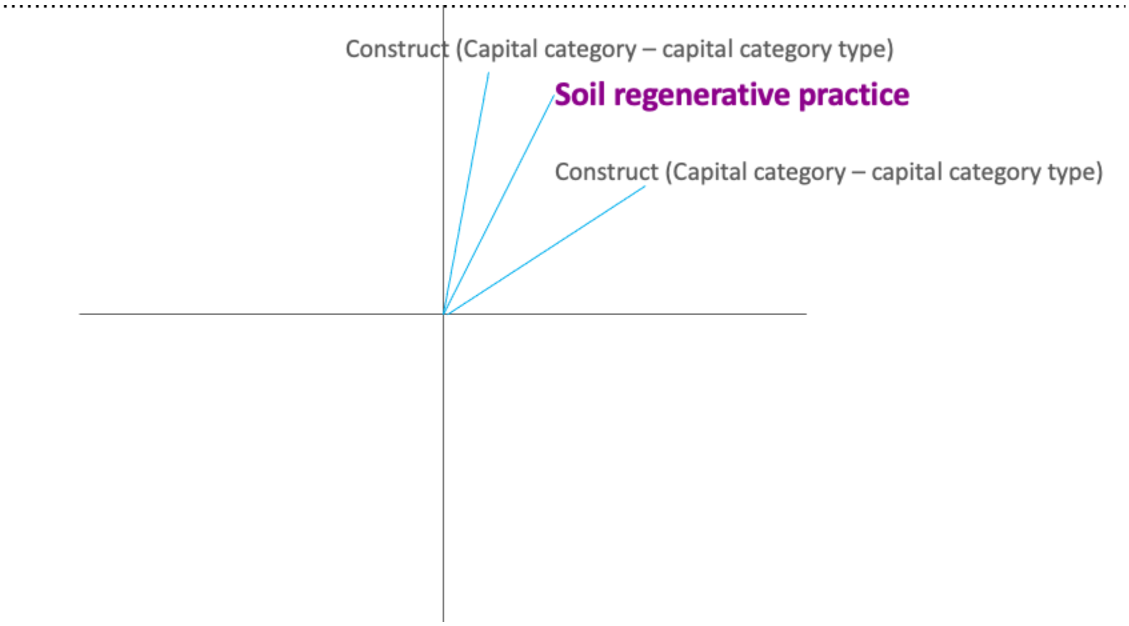


Figure 7. How I showed elements and constructs in my principal component analysis.

*Purple text indicates a soil regenerative practice (an element in the repertory grid), and grey text indicates the pole of a construct, with the capital category and capital category type I assigned to it in parentheses.*

I indicated each soil regenerative practice in bold, purple letters. Grouped around each soil regenerative practice in gray letters are the subcategories of winegrower constructs most closely related to the practice. The subcategories are outlined in the following format: "paraphrase of the construct (capital category – capital subcategory)". An example would be: "We don't know how to do it (Human – knowledge)".

### Is Social Capital Most Important for Regenerative Winegrowers? (H6)

My sixth hypothesis was that social capital enablers (as opposed to manufactured capital enablers) would be more important for regenerative winegrowers versus non-regenerative winegrowers. To test this hypothesis, I wanted to see if more of the regenerative winegrowers' constructs fell into the social capital category versus other capital categories. I performed a chi-square test of independence examining the relation between the number of soil regenerative practices adopted and number of constructs categorized as social, natural, human, financial or manufactured capital across all winegrowers.

To investigate the enablers and barriers to practice adoption further and provide a flavour of underlying factors, I added sub-codes to the capital constructs in Nvivo for the four types of capital most mentioned (social, natural, human, and financial capital) and did a thematic, tabular analysis of these to see what specific types of things winegrowers emphasized. I also did a graphical analysis of the number of regenerative practices adopted per winegrower certification type (Figure 5), to see if being biodynamic or organic meant that a winegrower was regenerative or not, and whether winegrowers with these philosophies actually were regenerative and could inform motivational factors (See methods, Table 8).

Table 8. Hypothesis 6: methodologies and analysis methods used.

<table>
<tr><th>Hypothesis</th><th>Methodology</th><th>Analysis method</th></tr>
<tr>
<td>In general, social capital enablers will be more important than manufactured or financial capital enablers for winegrowers that have adopted more soil regeneration practices (Wheeler & Marning, 2019)</td>
<td>Questions asked:<br>-Which of the following soil regeneration management practices do you already practice? (checklist)<br>-Barriers and enablers elicited via Repertory Grid.<br><br>N = number of constructs elicited</td>
<td>Content analysis, Tabular Chi square analysis
<table>
<tr><td></td><td colspan="3">Number of constructs categorized as:</td></tr>
<tr><td></td><td>Social capital</td><td>Human capital</td><td>Etc.</td></tr>
<tr><td>Non-regenerative (<4.35 practices adopted)</td><td></td><td></td><td></td></tr>
<tr><td>Regenerative (>=4.35 rpractices adopted)</td><td></td><td></td><td></td></tr>
</table>
Nvivo further sub-coding and thematic, tabular analysis of constructs. Tabular analysis of the number of practices adopted in terms of certification.</td>
</tr>
</table>

# Chapter III

# Results

My academic literature search to quantify the soil regenerative practices and determine which to use in the interviews with winegrowers yielded a total of 658 studies. 180 results came from the first and 165 from the second Google query. After analyzing these studies, 35 from the first and 13 from the second Google query were found to be relevant and have measurable soil carbon sequestration figures. I then found another 313 studies that were referenced in the studies from the Google query or recommended by others, 297 of which contained relevant and measurable carbon sequestration figures. In total, I found 345 (35+13+297) relevant soil organic C sequestration figures (Ancillary Appendix 1).

Table 9 shows how these measures found per study were distributed across the nine practices and across different land uses. The figures for non-chemical fertilizer were disproportionately higher than the others due to 209 carbon sequestration figures that were added from expanding the data in a meta-study on organic farming (Gattinger et al., 2019).

I found data for seven of the soil regenerative practices and two combinations of those where the practices could not be dissociated. Although both low traffic and redesigning the system at the landscape level appeared from the literature to be important practices for soil regeneration and for C sequestration specifically, no studies were found measuring C sequestration for them, so these practices could not be quantified.

Table 9. Number of studies found with carbon sequestration data (per practice).

| | Woody perennial land use | Arable land use | Total |
|---|---|---|---|
| **Single practices:** | | | |
| Agroforestry | 5 | 14 | 19 |
| Cover crop | 6 | 15 | 21 |
| Legume cover crop | 2 | 3 | 5 |
| Animal integration | 4 | 8 | 12 |
| Low traffic | 0 | 0 | 0 |
| Non-chemical fertilizer | 56 | 187 | 243 |
| Non-chemical pest management | 1 | 4 | 5 |
| No-tillage | 5 | 25 | 30 |
| Redesigning the system at the landscape level | 0 | 0 | 0 |
| **Combined practices:** | | | |
| Cover crop & Legume cover crop | 0 | 2 | 2 |
| Cover crop and No-tillage | 2 | 6 | 8 |
| **Total** | 81 | 264 | 345 |

### H1: All Regenerative Practices Observed Contribute to Carbon Capture

My first hypothesis was that in woody perennial and arable land uses, applying a cover crop would sequester the most carbon, but contrary to my hypothesis, I found no statistically significant difference between the seven practices with data, either for woody perennials (p=.17, ) or for arable crops (p=0.22), Ancillary Appendix 2).

For arable land use, the seven practices ranged from emitting 3.8 to sequestering 5.9 t C/ha/yr (both reported within the highly variable practice of non-chemical fertilizer, N=187), with the highest mean rate reported for agroforestry, at 1.22 t C/ha/yr (n=14 studies) (Figure 8). Agroforestry was closely followed by a cover crop with both non-legumes and legumes (1.20 t C/ha/yr) (although only across n=2 study samples). The use of a cover crop and no-tillage achieved the third highest mean at 1.01 t C/ha/yr (though also with a low number of samples, n=6). Non-chemical fertilizer and no-till had the lowest mean sequestration rates, at 0.48 (n=187 and n=25, respectively), followed lastly by legume cover-cropping at 0.48 t C/ha/yr (n=3).

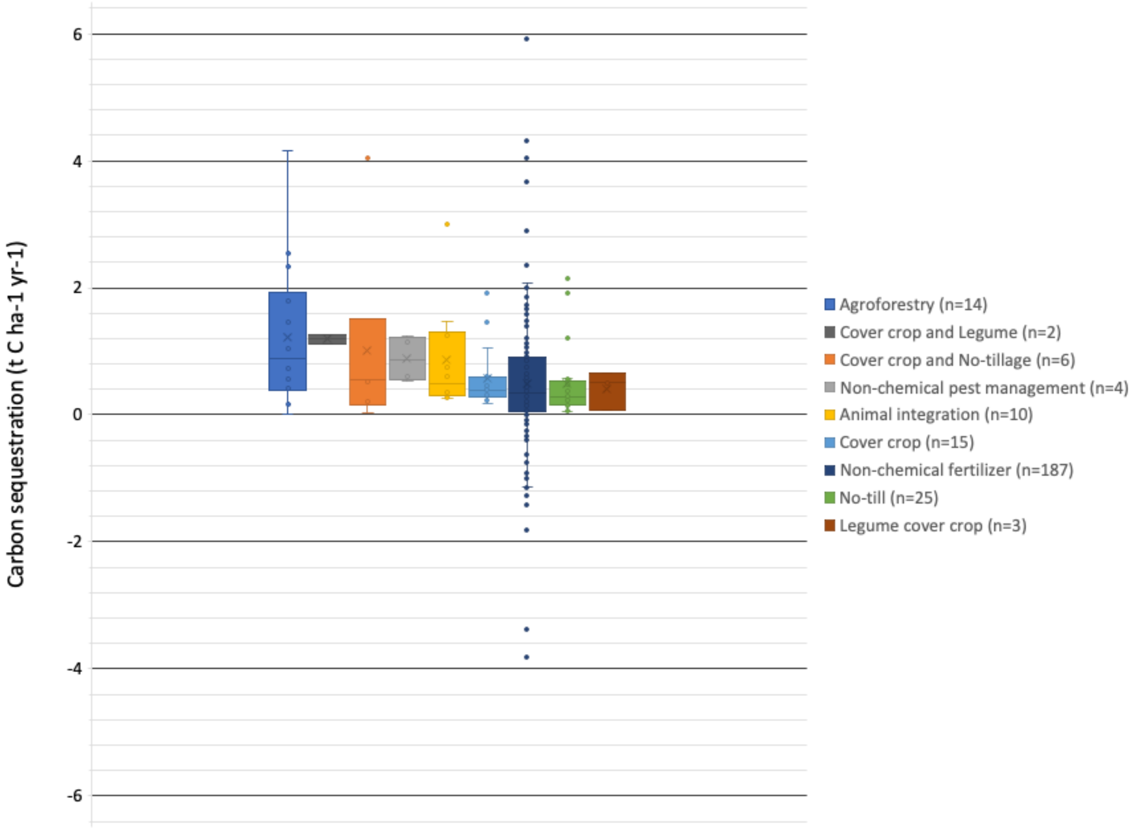


Figure 8. Below-ground C sequestration rates for practices on arable land.

*Positive values represent a below-ground carbon sink, while negative values can represent C emissions. The 'x' in each box is the mean. Raw data can be found in Ancillary Appendix 1.*

For woody perennial land use, the seven practices ranged from emitting 6.5 t/C/ha/yr with non-chemical fertilizer (n=57) to sequestering 4.93 t/C/ha/yr using animal integration (n=2), with the highest mean rate reported for animal integration, at 2.47

t/C/ha/yr (Figure 9). Animal integration was followed by non-chemical pest management (n=2) at 1.51 t/C/ha/yr, agroforestry (n=7) at 1.43 t/C/ha/yr, cover crop and no-tillage (n=2) also at 1.43 t/C/ha/yr, and the use of a cover crop (n=6) at 1.32 t/C/ha/yr. Non-chemical fertilizer (n=57) had the lowest mean sequestration rate, at 0.19 t/C/ha/yr.

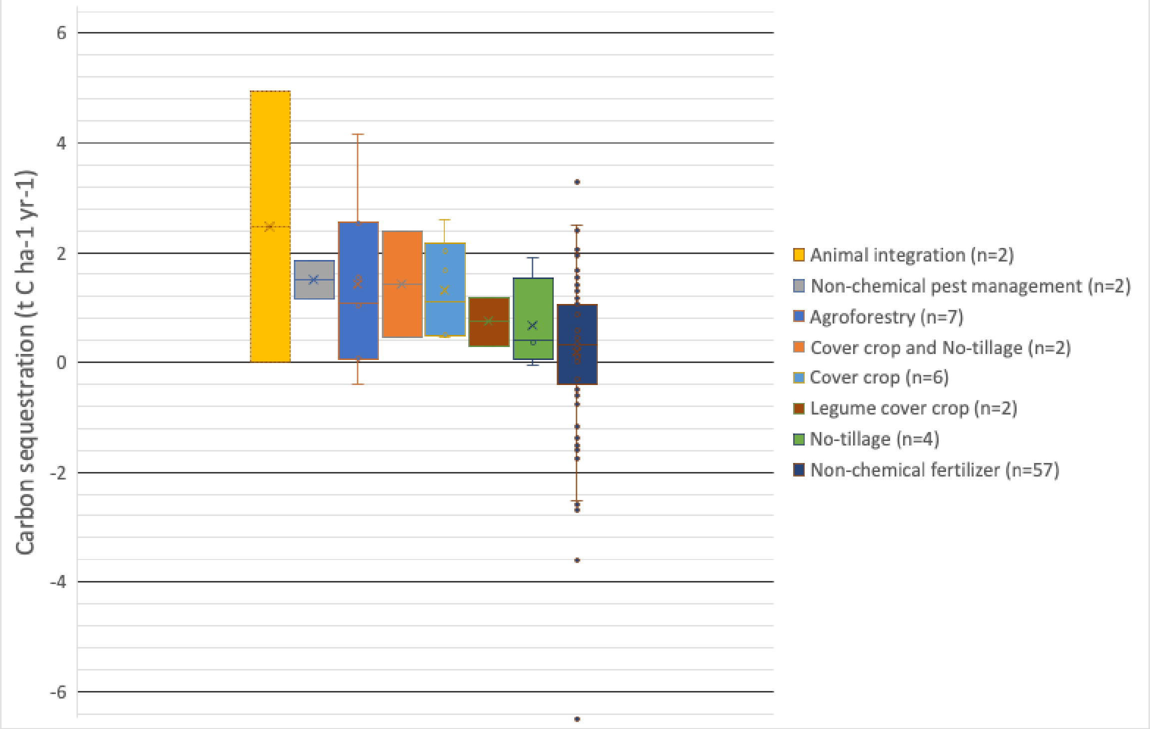


Figure 9. Below-ground C sequestration rates for practices on woody perennial land.

*Positive values represent a below-ground carbon sink, while negative values can represent C emissions. Raw data can be found in Ancillary Appendix 1.*

## Comparing Sequestration in Woody Perennial and Arable Land Use

I found no significant difference between the means of the different practices when comparing C sequestration in woody perennial versus arable land use (p=.19, Ancillary Appendix 2). In Figure 10, I charted these means against the global average for woody perennials from Payen et al. (2021), and for arable croplands from Zomer et al.

(2017) (Payen et al., 2021; Zomer et al., 2017). The mean values for practices in this study ranged from 0.13 to 2.47 t C/ha/yr, with slightly different effects on woody perennial versus arable land, though paired t-tests revealed that none were significantly different.

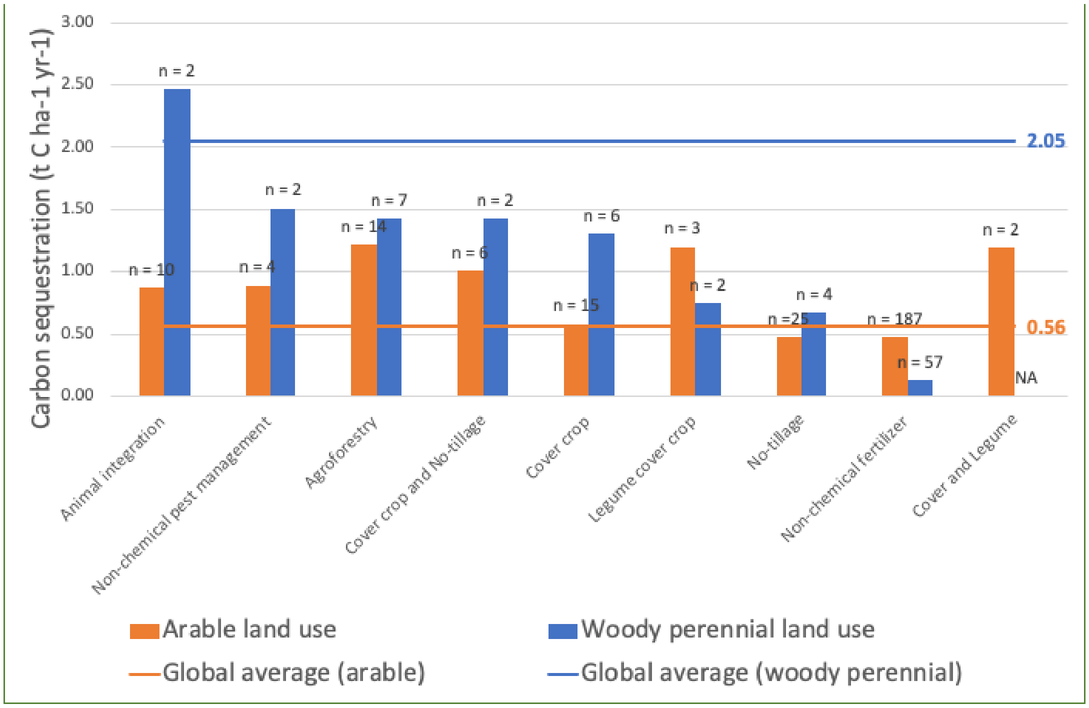


Figure 10. Average C sequestration per land use of various soil regeneration practices.

*Positive values represent a below-ground carbon sink. "n" equals the number of samples from studies where a measurable carbon sequestration figure was found. The global average for arable land uses comes from Zomer (2017) and for woody perennials from Payen (2017) (Payen et al., 2021; Zomer et al., 2017).*

## H2-H6: Winegrower Interview Results

My second hypothesis (H2) that social capital would be more important than manufactured capital for smaller winegrowers adopting regenerative soil practices was supported by the data. Having controlling ownership of a vineyard was significantly statistically related to being regenerative, which supported my third hypothesis (H3) that winegrowers that own more land adopt more regenerative practices. No significant statistical association was found between gender and the number of types of capital mentioned, thus refuting my hypothesis (H4) that social and human factors matter more to women winegrowers. Substantively, however, prior knowledge and competence (human capital) mattered more to women. In support of my fifth hypothesis (H5), agroforestry and redesigning the soil system at the landscape level were the hardest practices for winegrowers to adopt, followed by animal integration, low traffic and the use of a legume cover crop. Though not statistically significant, both regenerative winegrowers and non-regenerative winegrowers mentioned social capital more than financial or manufactured capital, in line with my hypothesis (H6). There were qualitative differences between the capitals that regenerative and non-regenerative winegrowers stressed: regenerative winegrowers stressed soil life and biodiversity, intrinsically-motivated by longer, ecological-economic equilibrium.

## Type of Constructs Elicited from the Winegrower Interviews

The largest shares (25.1% and 24.5%) of the constructs elicited from interviews pertained to natural and human capital, respectively. Constructs categorized as social and financial capital were 22.6% and 19%, respectively. The smallest share of constructs (8.4%) belonged to manufactured capital (Table 10).

Table 10. Percentage and type of constructs elicited from winegrower interviews.

| Capital type | % of constructs relating to the type of capital |
|---|---|
| Natural | 25.1% |
| Human | 24.5% |
| Social | 22.6% |
| Financial | 19.4% |
| Manufactured | 8.4% |
| Total | 100% |

*Note: a total of 155 constructs were elicited from winegrowers.*

H2: Manufactured Capital is Less of a Barrier for Small Winegrowers

My second hypothesis was that social capital would be more important than manufactured capital for smaller winegrowers to adopting regenerative soil practices, which was supported by the data. The relationship between vineyard size and types of capital constructs elicited was highly significant ($X^2$ (4, $N$ = 168) = 9.77, $p$ = .04). In line with my hypothesis, social capital appears to be more important than manufactured capital for smaller winegrowers.

My count of the number of constructs per type of capital and by vineyard size in each chi-square quadrant indicated that social capital was mentioned more than manufactured capital by larger vineyards. A content analysis of the constructs within each quadrant showed that social norms and having supporting institutions for stewardship were the issues most expressed by smaller vineyards, image and being able to gain or retain independence were the issues that larger vineyards stressed (Figure 11).

In terms of social capital constructs, smaller winegrowers found adoption easier when “other winegrowers do it” and “the practice is conventional and not ‘the city guy’s ideal’”. They saw continuing winegrower education and other ways of acquiring new knowledge about the practices as important, and some were more interested in adopting practices if they would help them obtain some kind of certification, such as the organic label.

Meanwhile, larger winegrower constructs expressed fear of losing their independence. They were more likely to adopt a practice when it “gives me sovereignty over the vineyard and frees me from big industry”, “can be programmed in advance without relying on human flexibility”, and “can be implemented by myself without relying on collaboration”. In terms of image, larger winegrower constructs included that a practice was easier to adopt if “it augments the beauty of the vineyard”, “it augments wine quality”, “consumers want and appreciate it”, “consumers can tell the difference”, and “it increases the brand image or reputation”. Consumer perception may therefore be a powerful lever in driving large winegrowers to adopt soil regenerative practices.

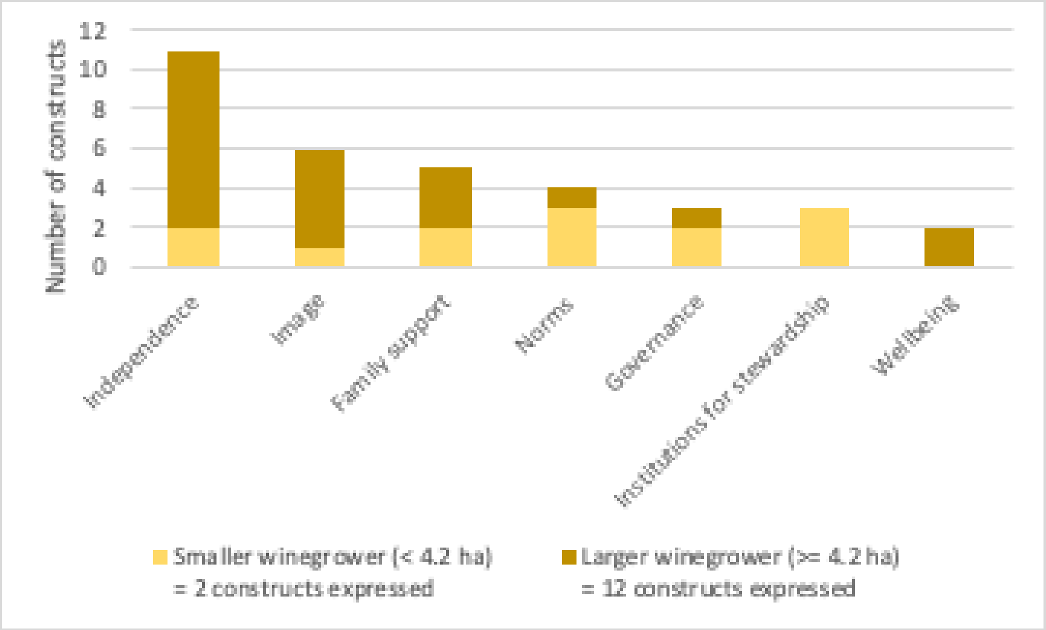


Figure 11. Types of social capital expressed by vineyard size.

Manufactured capital was the least mentioned of all capitals by winegrowers large and small (Table 10), indicating that social other capitals may be more important for winegrowers, in line with my hypothesis. However, manufactured capital was mentioned proportionally six times more by larger winegrowers as a barrier to adopting soil regenerative practices, so as I had guessed, manufactured capital seemed to be less important for smaller winegrowers.

Larger winegrowers tended to stress infrastructure as a manufactured capital barrier to practice adoption (Figure 12). Constructs relating to infrastructure for bigger vineyards can be summed up as ease of application when: “the practice can be applied to the entire winegrowing land (especially when it is more parceled)”; “the parcel/land is mechanizable or already suitable for the practice (e.g. row width, steel wire trellis)”; and “the vineyard has a small surface”. For some, a new practice was only conceivable if infrastructure does not have to be changed. For example, using legume cover crops or agroforestry between rows was only conceivable if a tractor could still pass within the rows to treat the vines when necessary and animal integration didn't cohabit well with steel wire trellises. Larger winegrowers who rely on investments in infrastructure to reach economies of scale may therefore end up locked into infrastructure and ways of doing things that prevent them from innovating.

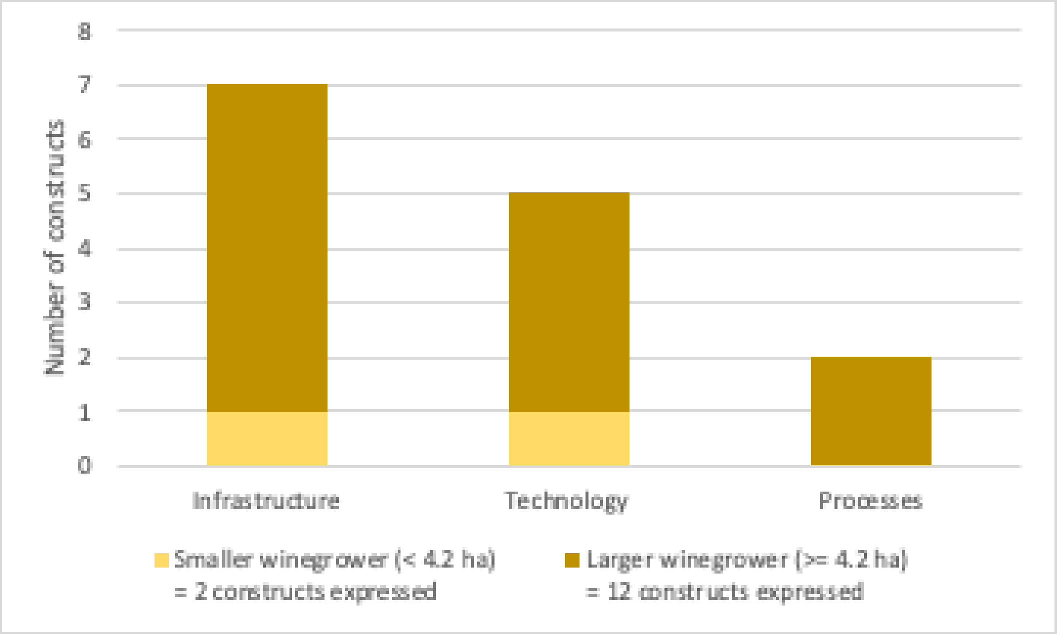


Figure 12. Types of manufactured capital expressed by vineyard size.

## H3: Owning 50% or More of a Vineyard Increases Practice Adoption

Having controlling ownership of a vineyard was significantly related to being regenerative ($X^2$ (1, N = 20) = 2.78, p = .09), thus supporting my third hypothesis. Therefore, winegrower land ownership may increase regenerative practice adoption. Simply owning a part of a vineyard (>0%) was not significantly related to being regenerative ($X^2$ (1, N = 20) = 1.65, p = .19), so how much of a vineyard a winegrower owns is important for regenerative practice adoption.

Table 11. Chi-square analysis: vineyard ownership and number of practices adopted.

| | Non-regenerative (<4.35 practices adopted) | Regenerative (>=4.35 practices adopted) | Row totals |
|---|---|---|---|
| Non-controlling owner (< 50%) | 8 | 6 | 14 |
| Controlling owner (>= 50%) | 1 | 5 | 6 |
| Column totals | 10 | 10 | 20<br>(Grand total) |

In my crosstab query of the capital types most mentioned by winegrowers in each of the chi square quadrants from Table 11, the non-regenerative, non-controlling owners stressed social and especially manufactured capital slightly more (Figure 13). Although the types of capital evoked were similar between quadrants, the underlying constructs were very different, with regenerative, controlling owners clearly showing sovereignty over their decisions to adopt practices within their own domain regardless of existing infrastructure, and were mostly limited by external forces. They knew how to implement regenerative practices and simply had to believe in them, and stressing soil life and long-term economic-ecological equilibrium. In contrast, non-regenerative, non-controlling owners were not necessarily able to make their own decisions or change existing infrastructure that isn't their own. They felt that they could only implement practices that they were already skilled in unless training was available, and worried more about the vine than about soil health or biodiversity. Financial viability was also stressed, without mention of sustainability in the long term.

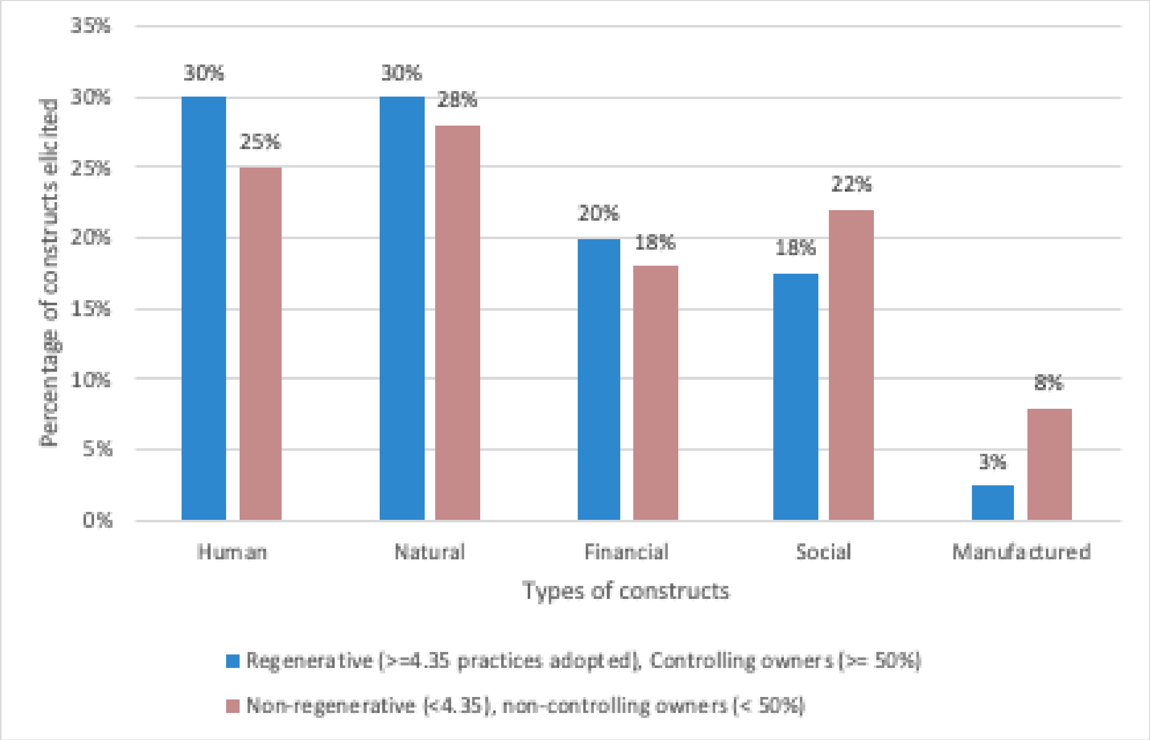


Figure 13. Constructs by ownership and number of practices adopted.

Non-regenerative, non-controlling owners were prevented from adopting regenerative practices because of infrastructure (manufactured capital) and lack of decision-making sovereignty (social capital). Practices needed to be "suitable for narrow rows", in line with "machines that we have had for 15 years", and "not requiring a change in viticulture/replanting". Non-regenerative, non-controlling owners also needed to be able to implement practices independently: only if “I can decide”, “I can implement it myself”, “I can do it alone”, or “does not require a big change in my organization”.

Meanwhile, for regenerative, controlling owners, infrastructure (manufactured capital) was not an issue and they were most motivated by practices that free them from external control (social capital). In terms of social capital, independence was also an issue but it manifested itself in terms of sovereignty vis-à-vis the world external to the vineyard: the practice “allows me to exist and have sovereignty over my vineyards”, “I don’t have to count on others”, it “frees us from dependence on suppliers and big industry (favors our independence)”, or “I can do it myself (not all other winegrowers have to adopt it for it to work)”.

In terms of human, natural and financial capital, the non-regenerative, non-controlling owners would adopt practices if staff could implement them with existing skills or with training. They worried mostly about the vine (“strengthens the vine”, “doesn’t compete with the vine”, “good for the vine”, “could increase beneficial predators”, “has other advantages beside benefits for the soil”, “has a direct and positive impact on the health and beauty of the grapevine”). Biodiversity or soil health were rarely mentioned. Practices had to be cost-free or financially viable, such as through subsidies.

In contrast, regenerative, controlling owners tended to know how to adopt the practices (“it’s part of our in-house knowledge”, “I have the competencies to put it in place”) and simply had to be personally convinced (“I am convinced”, “It’s a practice that I like”, “It’s part of my personal philosophy”, “I want to do it”, “my conscience feels it is the right thing to do”). They also stressed soil life and health (“the soil is right for the practice”, the practice “improves soil respiration including minerals and mycorrhizae”, “it increases soil life / biodiversity", or "it protects against erosion"). Financial capital motivation focused on sustainability issues such as "protecting the harvest" and "favoring an ecological-economic equilibrium".

*Impact of ownership type.* Another important finding was that having a landlord can negatively influence a winegrower's regenerative practices. My second cross-tab analysis showed that greater landlord involvement seems to relate to non-regenerative winegrowers, for five out of all nine landlords fell into the non-regenerative, non-controlling owner quadrant (Figure 14). Conversely, seven out of eleven regenerative winegrowers had no landlord involvement.

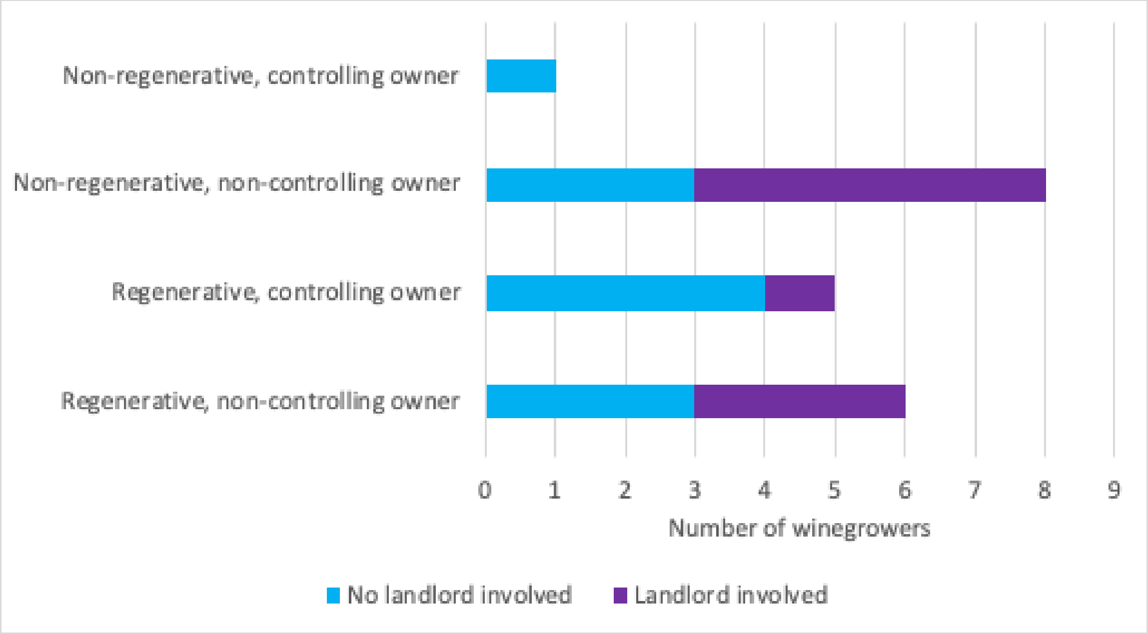


Figure 14. Landlord involvement by ownership and number of practices adopted.

*'No landlord involvement' includes the following ownership types: Self, Parent(s), Sibling(s) or Partner(s). 'Landlord involvement' includes these ownership types: Landlord(s), Landlord(s) & Parent(s), or combination Landlord(s), Parent(s) & Partner(s).*

H4: Women and Men's Motivation to Adopt Regenerative Practices

No significant association was found between gender and types of capital mentioned (X2 (4, N = 132) = 6.04, p = .19). However, women mentioned human capital twice as much as men, and men mentioned manufactured and natural capital twice as much as women (Table 12), thereby partly supporting my fourth hypothesis that social and human capital factors matter more to women winegrowers in adopting soil regenerative practices. There were interesting differences between the substance of the human capital constructs elicited from women versus men.

Table 12. Chi square analysis of types of capital constructs mentions by gender.

| | Financ. | Human | Manuf. | Natural | Social | Row totals |
|---|---|---|---|---|---|---|
| 12 Men | 20 | 18 | 10 | 30 | 19 | 97 |
| 12 Men - sample size adjusted (-33%) | 13 | 12 | 7 | 20 | 13 | 65 |
| 8 Women | 13 | 22 | 4 | 12 | 16 | 67 |
| Column totals (women + adjusted men) | 26 | 34 | 11 | 32 | 29 | 132 |

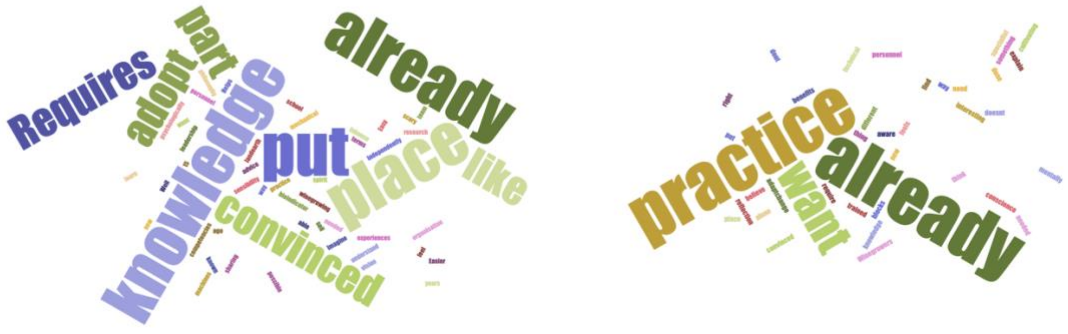
*Mentions by men (row one) were calibrated to allow for the 33% larger sample size (row 2) for comparison with women.*

The underlying human capital constructs expressed by winegrowers are gathered in Table 13. These served as the basis for the word clouds for women and men.

Table 13. Human capital constructs used in the word cloud, by gender.

| | |
|---|---|
| **Women** | Not scary (not new); It's what we learn at winegrowing school; Easy to adopt psychologically; Easier to put in place in terms of personnel and organisation; Well known; Can be put in place independently (requires no vision, leadership or team spirit); Part of our in-house knowledge; I am convinced; I have the competencies to put it in place; It's a practice that I like doing (not too mechanical); It's part of my philosophy; Requires a feel for the land/earth (sensibility); We already do it; I am convinced; We're already on the way; No more research, advice or sharing of experiences is needed to be able to adopt; I can imagine doing it; It's possible; Helps me understand my soil (bioindicator); I have the knowledge to do it; I want to do it; It was already like that 15 years ago (machines, knowledge) |
| **Men** | Can be done alone; I am convinced; We already do it; We want to do it; The practice is not new (doesn't require reflection); I want to do it (it's the how that blocks me); My conscience feels it is the right thing to do; I have the knowledge needed to put it in place; I am for it; It's something I think about; Winegrowers are already aware of the benefits; I don't have to mentally adapt/change to a different way of cultivating; My technical personnel can do it; I am already doing it; I find the practice interesting; I need a specialist to explain the practice to me; I am trained in it; I believe in it |

In terms of human capital, the words “knowledge” and “already” came up most for women, (Figure 15). Going back to the constructs in Table 13, ““knowledge” and “already” were related to subcategories of human capital including knowledge, understanding, sensibility, competencies for adopting soil regenerative practices. Knowledge could be in-house or learned at school. In comparison, the words “practice” and “already” came up most for men (Figure 15). When examining the constructs in Table 13, “practice” and “already” were related to already doing something and not having to reflect or mentally adapt/change to a different way of cultivating. For men, the tipping point for change centered around wanting to adopt a new practice that they found “interesting” and that a specialist could train them in.



**Women** **Men**

Figure 15. Wordclouds from constructs relating to human capital by gender.

*Note: wordclouds created via the Jason Davies Wordcloud generator (Davies, n.d.).*

In summary, women stressed human capital more, for already having the knowledge, understanding, sensibility, competencies was important to them for adopting soil regenerative practices. Men stressed human capital less, and seemed to prefer not having to change their ways or adapt mentally to a new practice unless it was made “interesting” for them.

### H5: The Hardest Practices for Winegrowers to Adopt

In support of my fifth hypothesis (H5), agroforestry, animal integration and redesigning the soil system at the landscape level were the hardest practices for winegrowers to adopt when comparing the geometric mean of the ratings across all the elicited constructs (in orange, Figure 16). Looking at the geometric mean for each element across all samples for the given construct “easy to adopt”/“not easy to adopt”, the mean winegrower also judged these three practices as well as low traffic as harder to adopt than other practices in general (in blue, Figure 16). Comparing the means for verification, redesigning the system at the landscape level and agroforestry remained the most difficult to adopt. However, animal integration was perceived as only moderately difficult to adopt compared with other practices, perhaps because many are already integrating grazing sheep in the winter or purposefully attracting birds for biodiversity, even though both animals can potentially harm the vines or grapes. Between the two means low traffic and the use of a legume cover crop were almost as generically difficult to adopt as animal integration.

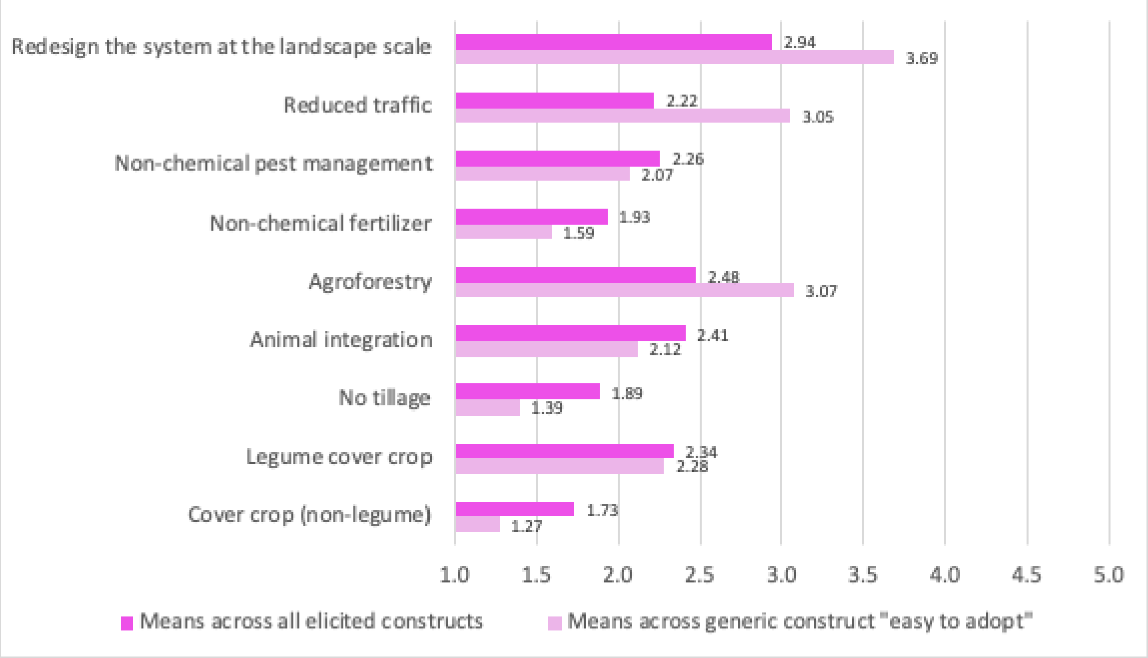


Figure 16. General difficulty of adoption of each practice.

*Key: 1 = easy to adopt, 5 = not easy to adopt.*

To understand what makes there practices so difficult to adopt compared others, I drew a three-dimensional principal components map (Figure 17). It shows how different practices were construed across the winegrower sample. Unsurprisingly given mean ratings, all five difficult-to-adopt practices fell closest to the “not easy to adopt” coordinate on the right-hand side of the map. These being clustered together indicates that winegrowers may construe them in a similar fashion. Why these practices might be construed as harder to adopt was then explored by looking at the construct categories that were closest to them on the principal component axes (Figure 17)

To the left of the y-axis, construct paraphrases are almost exclusively positive and enabling, such as “We are doing it already”. However, to right of the y-axis, with resigning the system at the landscape scale, agroforestry and animal integration, the constructs are almost exclusively negative, barrier constructs such as “We aren’t doing it yet”. Clustered between the three practices that were hypothesized to be the most difficult to adopt, we find the following perceived capital barriers:

- Social capital: lack of institutions for stewardship (lack of institutional support)
- Human capital: knowledge (not knowing how to do it)
- Manufactured: infrastructure (doesn’t suit the existing vineyard infrastructure)
- Financial: employees, time, cost, profit (need more resources or employees, no time or money for the practice, or fear that vine productivity may decrease)
- Natural: biological resources, land, general ecosystem, and water resources (fear that it might weaken biodiversity including the vine, fear that the practice might diminish soil health and structure, that it won’t protect ground or lake water, or that it might have a siloed or short-term impact on the ecosystem)

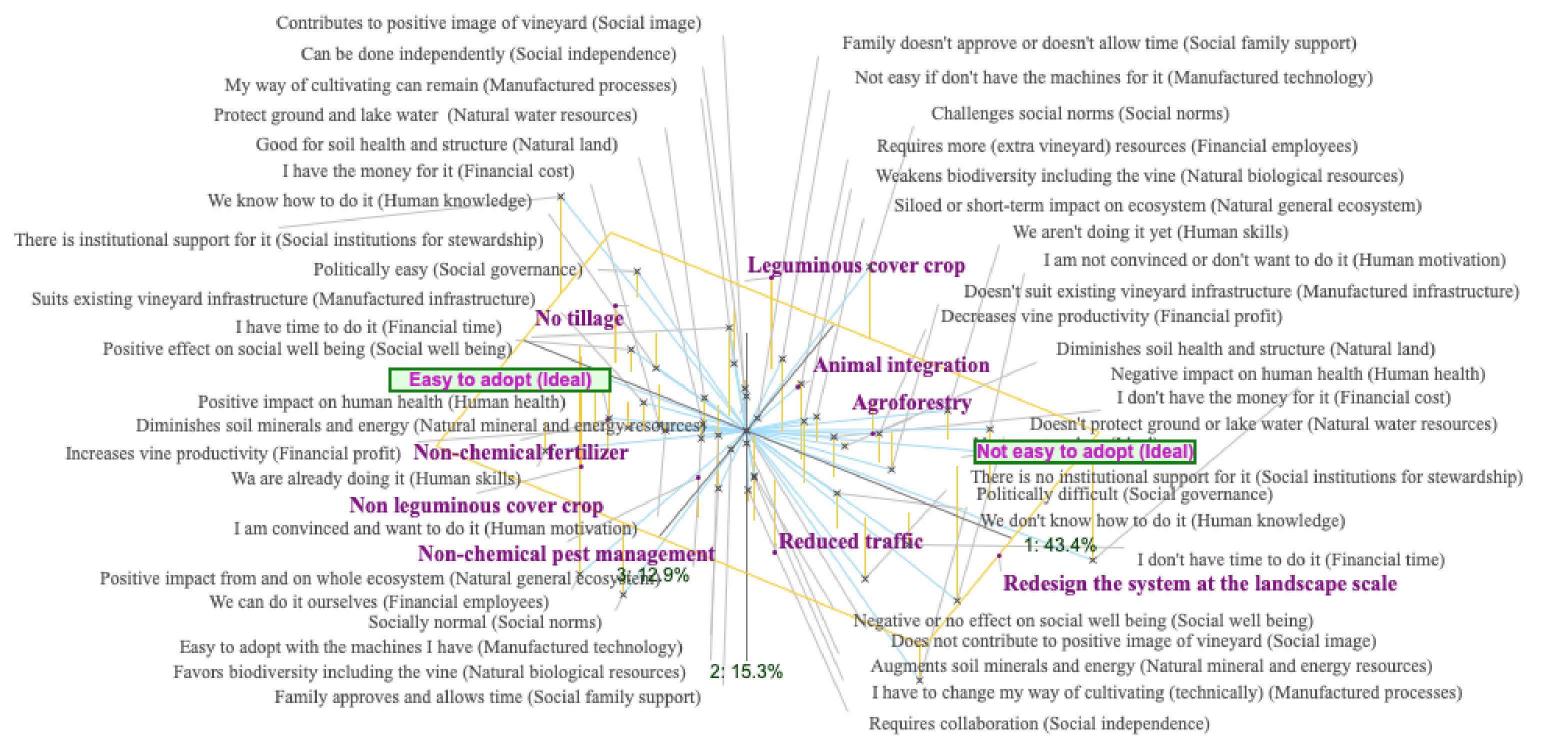


Figure 17. How different practices were construed across the winegrower sample.

*Note: Figure generated with Rep Plus (Shaw & Gaines, 2018). Soil regenerative practices are marked in purple and construct sub-categories are marked in gray according to the format: 'construct sub-category paraphrase (capital type – capital sub-category)'.*

For agroforestry, required infrastructure and landscape transformations do play a role as per my hypothesis in making agroforestry difficult to adopt. However, in terms of geometric distance on the PrinGrid Map, agroforestry lay closest to the natural capital construct category of fear of decreased vine productivity. The closest barrier to animal integration was not having to learn new skills, as per my hypothesis, that has been disassociated from winegrowing. Rather it was requiring more vineyard resources, such as needing more and specialized employees to care for animals. Finally, the closest barrier to redesigning the system at the landscape scale wasn't related to political maneuvering *per se.* Instead, it was about not having time, implying that the practice is perceived as being overly time consuming, for example by having to take part in meetings or discussions with neighbors or political authorities. It. Redesigning the system at the landscape scale also lay furthest on the grid from the notion that the practice could be done independently (Figure 17), yet Swiss winegrowers value independence - in this study, independence was the 9th most elicited topic from winegrowers out of the 24 capital topics. Therefore, redesigning the system at the landscape scale might be also perceived as a threat to independence.

### H6: Soil Life and Intrinsic Motivation for Regenerative Winegrowers

Though not statistically significant ($p=.94$), both regenerative winegrowers and non-regenerative winegrowers mentioned social capital more than financial or manufactured capital (Figure 18), in line with my hypothesis (H6) that social capital enablers are more important than manufactured or financial capital for regenerative winegrowers. Social capital enablers such as norms, independence, and image were mentioned more (more important) than manufactured capital by both regenerative and non-regenerative winegrowers.

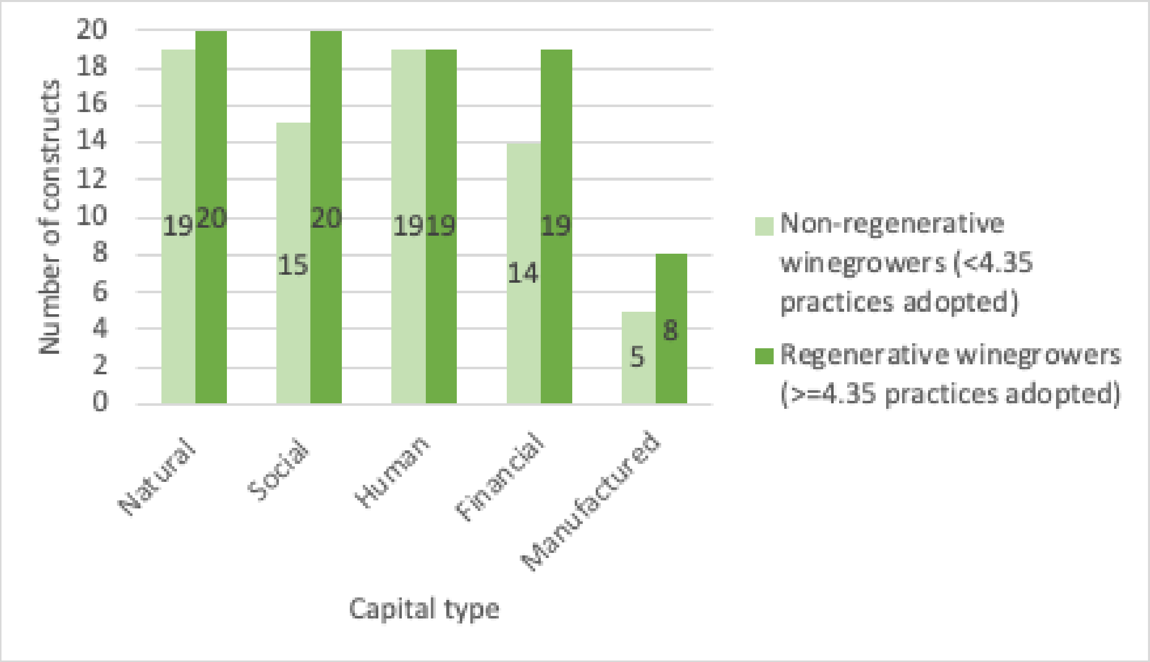


Figure 18. Number of constructs per capital: non- versus regenerative winegrowers.

Natural capital constructs had the most mentions and were related primarily to land (Table 14). Qualitatively and interestingly, non-regenerative winegrowers were most concerned with land issues such as soil structure and protection against erosion, while regenerative winegrowers spoke more of soil life and biodiversity (Table 14). Social capital factors for both groups related to norms, independence and image, and human capital constructs for both groups centered on motivation, knowledge and skills, though non-regenerative winegrowers stressed tradition and “the way they have always done things for generations”. Financially, both groups were motivated by cost savings, profit and time-savings. However, non-regenerative winegrowers mentioned only the extrinsic profit value “because the tourists ask for it”, whereas regenerative winegrowers had intrinsic and sustainable profit motivation, such as an increase in vine productivity, decreased harvest risk, and especially attaining a long-term ecological-economic equilibrium.

Table 14. Topics stressed by regenerative and non-regenerative winegrowers.

| | Natural (land) | Social (norms, independence, image) | Human (motivation, knowledge, skills) | Financial (cost, profit, time) |
|---|---|---|---|---|
| Non-regenerative | Land: soil structure and protection against erosion | - | Knowledge: tradition, “the way they have always done thing for generations” | Profit: (extrinsic), only because the tourists ask for it |
| Regenerative | Land: soil life and biodiversity | - | - | Profit - stressed disproportionately more by those who had adopted a greater number of practices: (intrinsic), increase in vine productivity or less risk for the harvest, and long-term sustainable ecological/ economic equilibrium |

Finally, it turned out that biodynamic and organic winegrowers were all regenerative (See Figure 5). While some conventional winegrowers were also regenerative, the biodynamic or organic winegrowers’ focus on soil life and biodiversity, and intrinsic motivation for longer-term ecological-economic equilibrium, may indicate that having biodynamic or organic philosophy or label may be an enabler for adopting regenerative practices.

In sum, social capital enablers such as norms, independence, and image were mentioned more than manufactured capital by both regenerative and non-regenerative winegrowers. However, natural, human, and financial capital were mentioned almost as much as social capital. There were qualitative differences between the regenerative and the non-regenerative winegrower constructs. Regenerative winegrowers stressed soil life as opposed to just soil structure, put less of a focus on tradition, and mentioned sustainable, intrinsically-motivated profit instead of extrinsically-motivated profit.

# Chapter IV

# Discussion

As set out in this study, I was able to quantify the soil regenerative practices that sequester the most soil organic C. On woody perennial land, animal integration had the highest mean sequestration rate, 64% higher than non-chemical pest management, the practice with the next highest impact. On arable land, agroforestry and the use of a cover crop with legume had the highest mean sequestration rates, between 18- 21% higher than the use of a cover crop and no-tillage, the practice with the next highest impact. However, both for arable and for woody perennial land uses, there was no statistically significant difference between the carbon sequestration rates of all the practices, nor for the means between practices for woody perennial versus arable land.

The barriers and enablers for winegrowers in the canton of Vaud, Switzerland to adopt these practices were related to vineyard size and percentage vineyard ownership, where smaller vineyards needed social reinforcement and access to information. Moreover, for controlling owners to be in constant contact with the soil and the terroir soil life, ideally as winegrowers themselves, was important for stewardship. The enablers were also different for women and men. For women, competency in a practice was an important enabler whereas men just needed the practice to be interesting. Agroforestry, animal integration, redesigning the system at the landscape level, but also low traffic were the hardest practices for winegrowers to adopt for perceived fear of decreased vine productivity, need for additional vineyard resources, or lack of time. Social, human, natural and financial capital were all important to regenerative winegrowers, and what characterized them was caring for soil life and intrinsic motivation.

## Regenerative Practices Contribute to C Sequestration in Concert (H1)

In theory, whether for either for arable or woody perennial land, all regenerative practices sampled can contribute to carbon sequestration in concert. Applying one practice over another yielded no statistically significantly different soil organic C sequestration.

My results showed that on arable land, all regenerative practices observed could sequester soil organic C, and agroforestry could sequester the most (1.22 t C/ha/yr). This finding is supported by the fact that agroforestry can increase soil carbon storage via net primary production, through the return of tree litter to the earth, root and rhizosphere decomposition, and non-tillage of areas around woody plants (Chenu et al., 2014). My hypothesis (H1) had been that applying a (non-legume) cover crop would sequester the most carbon, but the data did not show this, either for arable or woody perennial land.

Comparing my results to the literature, I found that my average results for arable land (0.79 t C/ha/yr across all practices) were roughly equal to the global average of 0.56 t C/ha/yr (Zomer et al., 2017). Individually, the average sequestration rates I found for most of practices were higher than the global average (see Figure 10). As an example, my average for agroforestry was more than double the global average.

My data indicated that combining practices may increase carbon sequestration. While applying a (non-legume) cover crop alone did not sequester the most carbon, combining a (non-legume) cover crop and legume yielded one of the highest mean sequestration rates (1.20 t C/ha/yr). This result is in line with recent studies that have shown that mixing grass and legume cover crops in vineyards worldwide with different soil types increases not only nitrogen but also soil organic carbon stocks (Ball et al., 2020), and appropriate grazing management can regenerate soil function to improve carbon sequestration (Teague, 2018). Combining a cover crop and no-tillage also yielded a high mean belowground sequestration value, at 1.01 t C/ha/yr.

The farmers in my study who combined practices could be seen as part of the second stage of the Soloviev & Landua (2016) framework for regenerative agriculture. The framework describes four stages of regenerative agriculture and can be used for evaluating how close a farmer is to Robert Rodale's vision. Briefly, the stages are functional, integrative, systemic, and evolutionary.

At the functional stage, farmers realize that agriculture is not at odds with nature and soil regeneration by tweaking existing practices and crops are the main focus (Soloviev & Landua, 2016). Applying several regenerative practices together facilitates farmer passage to the second, "integrative" stage, where agriculture is a force for good and multi-factor regeneration improves the vitality of entire living ecosystems beyond soil (Soloviev & Landua, 2016). At the third, systemic stage, people see themselves as part of nature, recognize the complexity of natural systems, and can see that the system benefits from disorder and disturbance, and that farms operate in an ecosystem that is larger than their farm/bioregion. In the fourth, evolutionary stage, regenerative agriculture is deeply woven into a larger culture of regeneration that includes songs, stories, myths, rituals, foods, ceremonies and music (Soloviev & Landua, 2016).

For farmers including winegrowers in Vaud, moving from stage two to stage four by recognizing themselves as part of nature, seeing that systems benefit from disorder and disturbance, and proudly making agriculture a social  and emotional pillar of society would shift agriculture from, as Soloviev & Landua (2016) put it, “a functional economic activity to a spiritually rich and emotionally fulfilling central heart of an agricultural community” (Soloviev & Landua, 2016).

The practice of using non-chemical fertilizer (n=187) had potentially meaningful outliers (Figure 8). It was the only practice with negative outliers, indicating a mysterious source of C emissions in some cases. Since many of the samples were expanded from a meta study on organic farming (Gattinger et al., 2019), I looked to the study which explained that the positive and negative outliers may be influenced by the amount of external carbon inputs. Whereas in my study non-chemical fertilizer was defined as the use of compost or waste products separately from animal integration or manure application, some samples in the Gattinger et al. (2019) study included organic fertilizer in the form of slurry or stacked manure as non-chemical fertilizer. Indeed, regenerative agriculture as a closed-loop system would tend to use only manure produced on the farm, but organic agriculture allows the import of external sources of manure and slurry which contain high concentrations of carbon. Net C emissions may be cause by the high carbon cost of imported slurry, while high C sequestration may be related to mixed farming techniques such as animal integration, organic matter recycling or forage legumes.

A few of the practices, such as no-tillage, also had potentially meaningful outliers (Figure 8). The high values in one no-tillage study were attributable to the application of mulches in addition to conservation or no-tillage, resulting in higher populations of earthworms and greater crop root density (Acharya, Kapur, & Dixit, 1998). In another, soil organic C rates were simulated and results were drawn from a short assessment time and considered as preliminary, because soil can take more than 30 years to reach an equilibrium under steadily-maintained no-tillage (Molina et al., 2017).

Agroforestry had potentially meaningful outliers as well. One high outlier at 4.16 t C /ha/yr sequestered was taken from an agroforestry study in Costa Rica for a coffee plantation newly combined with the *Erythrina poeppigiana*, a large tree used as a shade tree in coffee and cocoa plantations (Beer et al., 1990). This nitrogen-fixing shade tree produces a considerable amount of mulching material, from natural litterfall and pruning residues, which when recycled into the soil can double organic material inputs compared to natural forests and maintain soil nutrients (Beer et al., 1990). When nitrogen-fixing plants are included in rotation cover crop and no-tillage conditions such as would be the case in a shade tree and cocoa plantation, soil organic C increases significantly (Jat, Wani, & Sahrawat, 2012). This biomass and nutrient return to the soil accounted for the high soil organic material increase.

Missing or small sample sizes for six practices hampered analysis; more studies are needed to assess carbon sequestration potential in vineyards for practices including the combined use of a non-legume and a legume cover crop (n=2), the use of a legume cover crop (n=3), non-chemical pest management (n=4), and animal integration (n=10). Moreover, no data samples were found for low traffic and redesigning the system at the landscape level. However, low traffic and redesigning the system at the landscape level should not be discounted as regenerative practices, as studies indicate that they can be highly beneficial. For example, Asbjornsen (2014) posits based on earlier studies that in terms of redesigning the system at the landscape level, placing perennials such as grapevines or trees on land that is vulnerable to erosion can enhance soil carbon retention (Asbjornsen et al., 2014).

In sum, while there were no significant differences in C sequestration found for practices in the complete dataset as a whole, looking at individual studies and the mechanisms behind them suggests that mixed farming, animal integration (also as a source of non-chemical fertilizer), and nitrogen-fixing trees or nitrogen-fixing legume cover crops are general best practices to increase carbon sequestration in arable land. Combining practices together rather than practicing monoculture can help farmers combat climate change and biodiversity loss and help them move to the second, multifunctional evolutionary stage of regenerative farming.

### Practices Contribute Differently to C Sequestration in Vineyards

Woody perennial (including vineyard) soil responded differently to general agricultural soil, and in my results all practices except two sequestered more carbon in woody perennial than arable cropland. The results were not statistically significant. However, animal integration yielded more than twice the carbon sequestration in woody perennial as in arable cropland (Figure 9). The use of a cover crop sequestered 39% and non-chemical pest management sequestered 26% more in woody perennial than arable cropland. Agroforestry, the use of a cover crop and no-tillage, and no-tillage all had greater mean soil C sequestration with woody perennial land. Indeed, soils are so exhausted and chemical pesticides so prevalent in viticulture that any addition of manure or soil life may make a big difference compared with arable crops.

The difference between the impact from animal integration on woody perennial versus arable cropland deserves a closer look. While the sample size for animal integration for viticulture was small (n=2) and in one study manure application was used as a proxy for animal integration, my results indicate that the practice can play a key role in soil carbon sequestration and thus vineyard soil health. The variation among samples was high, however.

In one animal integration study spanning one year, the 0.09 t C/ha/yr sequestered was measured in a no-till, grass vineyard in Italy with sheep grazing in the winter compared to a neighboring pasture with sheep on it in the vicinity (Francaviglia, Renzi, Ledda, & Benedetti, 2017). In this particular case, the soil may have reached a steady state or elsewise already been carbon-saturated for sequestration to have been so low (Gubler, Wächter, Schwab, Müller, & Keller, 2019), or the length of time that the sheep were one the land may not have allowed for much manure addition. Likely, however, is that as tends to happen, a short-term variation in soil organic C occurred at the time of measurement, highlighting the importance of longer-term studies over decades (Gubler et al., 2019).

The other sample study of animal integration (an experimental, 10-year study of hickory tree plantations in China with manure mowing used as a proxy for animal integration) found a high sequestration rate of 4.93 t C/ha/yr. Although a proxy, the study indicates that integrating animal resources increases carbon content, and this carbon increase can have a positive effect on network complexity of soil communities, including keystone microbe and mycorrhizae species that play an important role in soil life, plant life, and carbon cycling (Xue et al., 2020).

Animal integration offers benefits beyond carbon sequestration, too. For example, cattle management in vineyards can aid in pest and fire prevention, while at the same time reducing fertilizer and pesticide requirements (Barbosa et al., 2019). Studies have demonstrated that including perennial forages and returning manure to croplands through animal integration can also increase soil health by reducing nitrate leaching into groundwater, reducing erosion, increasing soil carbon and water retention, fixing more nitrogen, reducing pests and more (Asbjornsen et al., 2014).

My study indicates that sequestration with non-chemical pest management in woody perennial may be higher than in arable cropland**.** This difference may be because grapevines otherwise tend to grow in an extremely pesticide-dependent monoculture environments, where soils are depleted and in need of soil organic C build-up (Chen, Chen, Chen, & Huang, 2019). Monocultures contribute to the depletion of soil organic C because they tend to have less plant diversity – and thus less microbial biomass (Chen et al., 2019). However, where underground microorganisms and other life, including mycorrhizae, are allowed to flourish, such soil microorganisms play a critical role in soil respiration and the cycling of carbon (Chen et al., 2019). Allowing biodiversity to regenerate can even help reinforce vineyard resilience to pests, because biodiversity can regulate the ecosystem and make it difficult for pests to establish (Guo, Fei, Potter, Liebhold, & Wen, 2019). Therefore, practicing non-chemical pest management and allowing microorganisms and plant diversity to flourish in vineyards is key for vineyard sustainability.

Indeed, mixed farming that includes animals is known to have benefits (Figure 19). Thinking of practices and elements of a vineyard as part of a system rather than in silos may help to understand why some practices, such as agroforestry, may have been found to have different effects in woody perennial versus arable cropland. The influence of woody perennials on soil fertility in agroforestry, for example, is synergistically coupled with their impact on hydrologic and carbon sequestration services (Asbjornsen et al., 2014). Moreover, topsoil organic C has been found to be higher in traditional polyculture agrosystems, such as olive-grapevine groves in Italy, than in either crop grown intensively alone as a monoculture (Brunori et al., 2020). The carbon sequestration results for agroforestry in woody perennial versus arable cropland could have been even higher, for the high point outlier for agroforestry in arable land use was taken from a study regarding a coffee bean crop, a perennial like a grapevine that could have been classified here as an orchard or used as a proxy for viticulture. It may be that the difference in carbon sequestration from agroforestry between woody perennial and arable crops is negligible, and that the practice simply has a roughly equally positive effect in both cases.

Any combination of no-tillage and the use of a cover crop appeared to have a slightly greater effect in woody perennials (Figure 10). Grapevines, as a woody perennial, can for example develop symbiotic arbuscular mycorrhiza over time that enhance the vine’s ability to obtain water and nutrients from the soil, and at the same time can collect carbon from plants to store below ground (Trouvelot et al., 2015). Contrast this mycorrhizal development in viticulture with annual arable cultures whose roots may be pulled out of the soil for the soil to then be tilled before the next planting. No tillage allows mycorrhiza to form without disturbance, and selected neighboring weeds (such as interrow grass cover) may promote a different set of mycorrhizal fungi to help colonize grapevine roots (Trouvelot et al., 2015). Cover crop and no-tillage may therefore be beneficial for mycorrhizal fungi to develop and contribute to carbon sequestration, especially in perennial crops like grapes.

Conversely, legume cover-cropping and non-chemical fertilizer had a greater effect in able land uses (Figure 10). Although my data indicated that the carbon sequestration benefits of legume cover crops may be smaller in viticulture versus agriculture generally, legume cover cropping has longer-term benefits. For example, grass cover crops compete with vines for nitrogen, an important nutrient. Legume cover crops, however, increase soil nitrogen, even if it takes time for the nitrogen to become available for vine uptake (Abad, Mendoza, Marin, Orcaray, & Santesteban, 2021).

For woody perennials, only non-chemical fertilizer had a sample size large enough for its quartiles and outliers to be meaningful (Figure 19). The reason for the negative outliers indicating a source of C emissions, at  -2.59, -2.69, -3.6, and -6.5 t C/ha/yr, was not made explicit from the sample studied whose focus was not on soil organic C (Vavoulidou, Coors, Dózsa-Farkas, & Römbke, n.d.; (Benitez, Nogales, Campos, & Ruano, 2006), but may result from a lack of animal or manure integration, or from emissions due to compost or trimming decomposition (Figure 19).

## Towards a Taxonomy of Soil-Regenerative Viticulture Practices

Applying one practice over another yielded no statistically significantly different effect in soil organic C sequestration, either for woody perennial or arable cropland. Although only animal integration with woody perennials reached the average annual potential soil organic C sequestration rate of 2.05 t C/ha/yr for viticulture calculated by

Payen (Payen et al., 2021), all seven practices measured contributed to below-ground carbon sequestration on average. Although yet to be quantified, low traffic and redesigning the system at the landscape level may also provide soil organic C sequestration.

Although none of the means were found to be significantly different, in terms of absolute mean values, soil regeneration strategies for woody perennials might be slightly different to arable crops. Animal integration, non-chemical pest management, agroforestry, cover crops and no-tillage, and cover crops all sequestered more carbon in woody perennial than arable cropping systems (Figure 10). However, these results are based on a small number of samples (n<6) and would need to be verified.

Finally, combining soil regenerative practices that foster biodiversity rather than applying them individually may sequester more carbon. The long-term Jena Experiment shows that carbon storage strongly increases with increasing plant species richness (Weisser et al., 2017). Applying diverse cover crops, agroforestry, animal integration, non-chemical fertilizer, non-chemical pest control, and redesigning the system at the landscape level can all contribute to species richness. Moving away from species-poor monocultures, shade-grown (using non-chemical pest control) perennial cultures can be managed to produce multiple, biodiverse products including fruits, herbs, and medicinals (Asbjornsen et al., 2014). Research is also emerging on the greater resilience to climate change of perennial plant communities with high species diversity, under the assumption that within this diversity there is a greater probability that species exist with traits adapted to climate change (Asbjornsen et al., 2014).

Drawing together my findings, I visualized a framework using Vensim (Julian Smart et al., 2019) for how the different soil regenerative practices and their opposites affect biodiversity, soil carbon sequestration, long-term vineyard productivity, and human health and wellbeing (Figure 19). In the rectangles are stocks such as biodiversity, soil organic C, or human health and well-being. The different regenerative practices, which I have C sequestration data for in this study, act as levers to increase the rate of soil organic C sequestration (inflow). Meanwhile, their opposites, for which I don’t have C emission data, act as levers to increase the rate of carbon emissions into the atmosphere (outflow). For example, as the reinforcing ‘+’ arrows from animal integration show, well-managed animal integration contributes positively to biodiversity and to increasing the carbon sink rate (which in turn augments the soil carbon stock). In contrast, high nitrogen fertilizer input tends to decrease biodiversity, as shown by the negative arrow. Note the reinforcing loop with two positive flows between long-term vineyard productivity and human health and well-being, showing that the two are mutually dependent on one another, notably when the human in question is the winegrower.

To sum up, adopting soil regenerative practices can help regenerate degraded biodiversity, increase soil carbon sequestration for climate mitigation, ensure long-term vineyard productivity, and secure human health and wellbeing. On arable croplands, agroforestry may sequester slightly more carbon, and in woody perennials, animal integration may sequester slightly more than other practices. However, any soil regenerative practice can increase soil C sequestration, and mixing practices can further

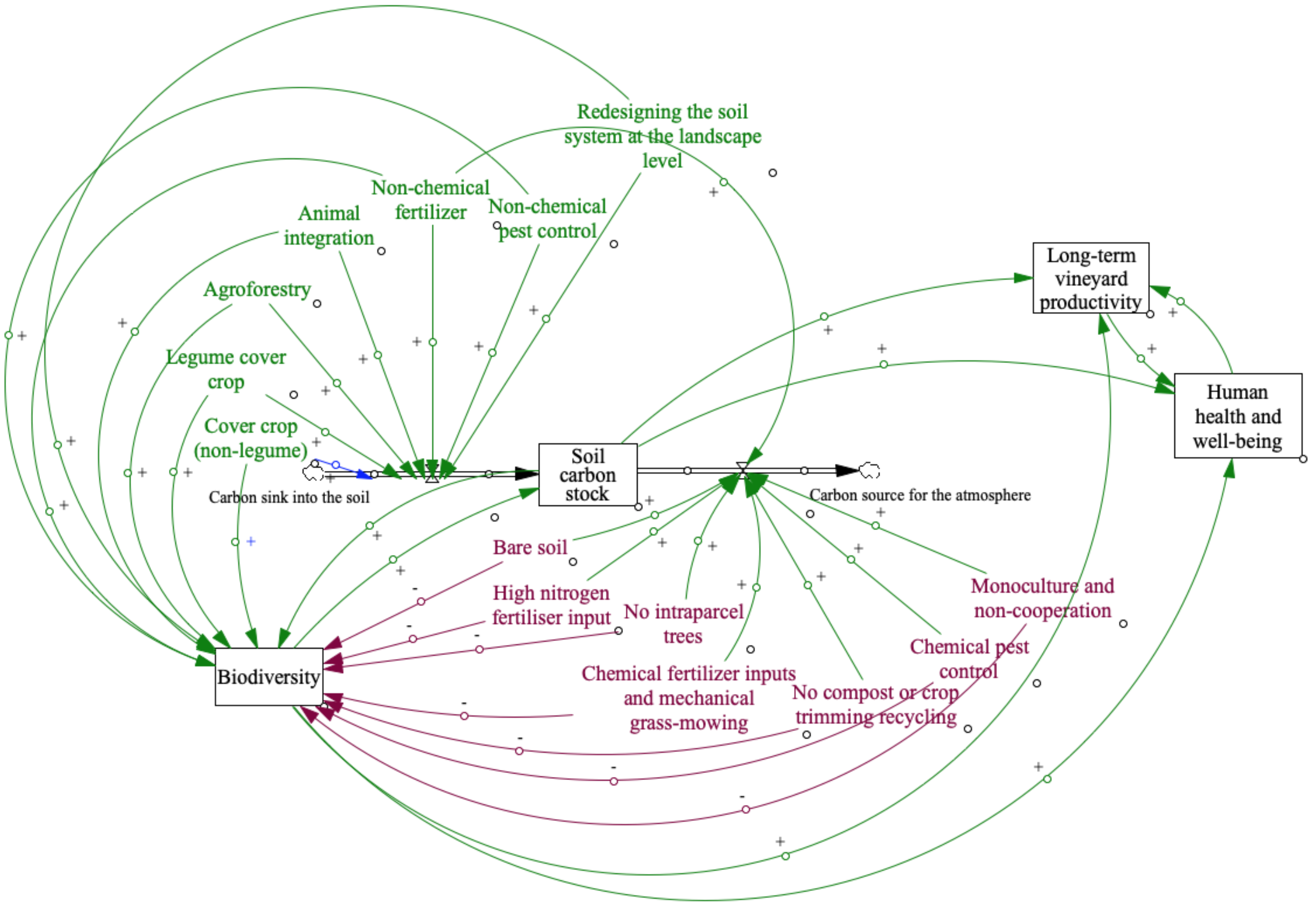


Figure 19. Impacts of regenerative versus non-regenerative farming.

*Note: author's own drawing.*

strengthen carbon sequestration. Woody perennial soil responds differently than arable crop soil, and many regenerative practices can sequester more soil organic C in woody perennials than other arable land used. Moreover, even though reversing biodiversity loss is central to regenerative agriculture, it is often disregarded in favor of other soil health indicators (such as carbon sequestration) when discussing recommended practices (Giller et al., 2021). However, carbon sequestration is just one piece of the puzzle in a healthy soil ecosystem.

Woody perennials such as grapevines are therefore a particularly favorable crop to lead the way for regenerative agriculture. Although all regenerative practices work best in concert, winegrowers considering an incremental approach might consider mixing, and going a middle way between sequestration impact and perceived ease of adoption. Figure 10 shows average soil C sequestration of practices in viticulture, and Figure 16 shows perceived difficulty of adoption across the generic construct “easy to adopt”. The following might be a middle path adoption sequence:

1. Cover crop and No-tillage (easy to adopt, high C sequestration, and adopting both together sequesters more C than each adopted in silos)
2. Non-chemical pest management (moderately easy to adopt, and high C sequestration)
3. Non-chemical fertilizer (easy to adopt, though low C sequestration)
4. Animal integration (slightly difficult to adopt, but very high potential C sequestration)
5. Agroforestry (difficult to adopt, but high C sequestration potential)
6. Legume cover crop (moderately difficult to adopt, and moderate C sequestration)
7. Reduced traffic (difficult to adopt, unknow C sequestration potential)

8. Redesigning the system at the landscape scale (perceived as most difficult to adopt, unknow C sequestration potential)

## Size, Ownership and Other Enablers of Soil Regenerative Practices

Having a smaller vineyard, being a winegrower with controlling ownership, and – for women winegrowers – empowerment all seemed to be enablers for adopting soil regenerative practices. For overcoming the hardest-to-adopt practices, providing knowledge-sharing platforms for winegrowers, tailoring research and training, and improving collaboration may be crucial.

### H2: Smaller Vineyards May be More Agile in Adopting Practices

My research indicates that smaller vineyards may be better suited for soil regeneration. Here I will outline how they can produce more, have less infrastructure barriers to overcome, and contribute to local food sovereignty. Being small, local and regenerative may also be a consumer value proposition. However, smaller winegrowers need social reinforcement and opportunities for knowledge exchange in order to more swiftly adopt regenerative practices.

Firstly, I found that small vineyards may be more agile in adopting soil regenerative practices, especially because they tend to have less “locked-in” infrastructure. However, they require social reinforcement and access to information about new practices. This is important because not only do small farms make up most of the world’s farms, but they have been found to produce higher yields and more biodiversity than larger farms, making small farms a pillar of sustainable - and indeed regenerative - agriculture development (Ricciardi, Mehrabi, Wittman, James, & Ramankutty, 2021). These new findings from the Ricciardi et al. (2021) study, a meta-analysis of worldwide, peer-reviewed studies that include farm size and production outcomes (n=218), may be surprising in view of conventional arguments that large monocultures are more efficient for feeding the world. However, conventional farming practices for enhancing productivity since the 1960s have largely been the cause of environmental degradation and soil exhaustion, and are therefore no longer sustainable (Rose et al., 2019). Besides, based on an analysis by Rapsomanikis (2015) of smallholder farm data in nine countries, there is a practically universally observed inverse relationship between farm size and productivity (Rapsomanikis, 2015).

Small-scale farming also provides an opportunity for food sovereignty: local, regenerative food systems that are run by and for its citizens (Pimbert, 2015). This study indicates that bigger winegrowers are deeply concerned about losing their sovereignty and independence, but some are already locked into expensive external inputs. In his study of Swiss farmers, Home et al. (2019a) also found that some Swiss farmers are afraid of losing their sovereignty and being limited by external rules and regulations (imposed for example by organic certification bodies), and this fear bars them from adopting new practices (Home et al., 2019a). This fear may stem from the experience of adopting others technological practices that create a dependence and have been at the heart of the agricultural development crisis that manifests itself through declining productivity and profitability, and has even led in many instances to farmer suicides (Srijit Mishra, 2008). However, Home et al. (2019a) found that these fears may be unfounded because farmers adopting ecological practices actually tend to gain self-determination and independence from external forces, such as suppliers of synthetic inputs (Home et al., 2019a).

Sovereignty – being able to govern oneself as one chooses – can be constrained by infrastructure, however. I found that bigger vineyards are dependent on built infrastructure such as the arrangement of land parcels, row width or cultural practices such as the steel wire trellis. In the renewable energy sector, reaching a certain size through economies of scale often depends on built-up infrastructure including technology that helps efficiency gains, but the inertia of the infrastructure locks the system in a given direction and ties it to other market actors (Klitkou, Bolwig, Hansen, & Wessberg, 2015). Bigger vineyards may therefore be resistant to adopting practices that would require them to change that infrastructure or services they now depend on, even though they may actually compromise the sovereignty they so fear losing. For example, *animal integration* may be more difficult logistically when parcels are many and geographically dispersed, and changing row width or planting trees in the middle may mean expensive tractors or machinery that has been invested in cannot pass through. Conversely, smaller winegrowers in my research did not evoke these infrastructure barriers nor a fear of losing their independence.

Home et al. (2019a) also found that smaller farms have a lower barrier to conversion to ecological practices, attributed to lower transaction costs associated with infrastructure and services. Therefore, smaller winegrowers may have unique advantages for resilience in a sustainable world. Indeed, smaller winegrowers may not yet be locked into infrastructure and they may have natural autonomy from foreign markets. They may depend less on infrastructure inputs such as technology or chemical pest management, as well as on foreign markets to generate a profit, and therefore are more apt as a regenerative, closed-loop system. They may therefore be less reliant on global agri-food systems and supply chains controlled by a few international corporations that undermine local autonomy and sovereignty (Pimbert, 2015). For farmer sovereignty, food systems – including production and consumption - need to be local and regenerative, and a shift from large-scale to small-scale and decentralized is necessary so that farmers can focus on “doing more with less” (Pimbert, 2015).

“Doing more with less” may even be a selling point for smaller winegrowers. The wine industry has found it difficult to switch from production- to marketing-orientation, even though honoring terroir and place of origin for smallholder, premium wine may seem like a logical added value (Johnson & Bruwer, 2007). Research indicates that consumer perceptions of quality are more positive when wineries use strong and positive regional branding images, suitably tied to terroir and therefore to the soil (Johnson & Bruwer, 2007). There is growing consumer interest in sustainable wine as an artisanal and authentic product as opposed to an industrial one with negative externalities (Baird, Hall, & Castka, 2018). Small winery tasting rooms also have the unique advantage of being able to provide a doorway to vineyard visitation and outdoor festivals to showcase sustainability for the consumer (Baird et al., 2018). Such small winery experiences can highlight regenerative practices such animal integration, agroforestry, or non-chemical pest management. And soil regenerative winegrowing certification, provided by supporting institutions for stewardship, could help put the social stamp of approval on regenerative winegrowing that winegrowers in this study expressed as an incentive for practice adoption. However, as my research showed (Figure 5), mainstream certification labels don’t necessarily capture soil regenerative practice adoption.

In my findings, the barriers to success that smaller winegrowers needed to overcome to adopt regenerative practices were related to social norms that reinforce practices (for instance, “other winegrowers do it”) and having institutions for stewardship (ways to acquire new knowledge about regenerative practices, such as continuing education, or stamps of social approval, such as certification). To help them overcome these barriers, smaller winegrowers need tools to face social norms and access knowledge about new practices, as well as certification programs that endorse regenerative practices. Rust et al. (2020) also found that smallholder farms need access to information and networks in order to adopt sustainable agricultural practices (Rust et al., 2020). Farmers have been found to acquire new knowledge unidirectionally through “knowledge transfer” from media or other farmers, or multi-directionally through “knowledge exchange” involving co-production and interaction with other farmers or other actors (Rust et al., 2020). The latter “knowledge exchange” approach may be more appropriate for soil regenerative practices because as per Rust et al., “the uptake of sustainable soil management practices is inherently a social and a learning process” (Rust et al., 2020, p. 3). Co-production dialogues can also be a way to provide visibility into “what others are doing”, including more innovative practices.

To conclude, smaller vineyards may be more agile in adopting soil regenerative practices, but they need opportunities for knowledge exchange, both for access to information and networks but also to reinforce that social norms may be changing among other winegrowers. Smaller winegrowers may also need ways to positively market the soil regenerative practices they have adopted (through certification or otherwise). Finally, smaller winegrower should avoid investing in too much locked-in infrastructure that can prevent bigger winegrowers from innovating and being resilient in a constantly evolving environment.

### H3: Controlling-Owner Winegrowers May Be More Regenerative

My research found that a winegrower being a controlling owner was significantly related to adopting more regenerative practices. Below, I will explain why a landowner's link with the soil as a winegrower is important, because owners have longer-term values, including soil health, and care more about non-financial benefits. I will also discuss how owners that are not the winegrower can encourage soil stewardship.

It is important for vineyard owners to be in constant contact with the soil and the terroir. Olivier Tèzenas, owner-winegrower from an eight-generation family vineyard in Provence, France, said: "there are two kinds of owners: those that aren't winegrowers themselves, and can sell to anyone on a dime, and those that are winegrowers, who live on vineyard and for whom the value of the land is tied to the wine they produce" (Guerrin, 2021). In a context of impending climate change and biodiversity decline disasters, for winegrowers to have controlling ownership of the land may be vital for soil regeneration. My research findings indicated, for example, that soil life and health was more important for controlling owners.

Land tenure security motivates farmers to invest in soil health (Walmsley & Sklenička, 2017), and corresponding to the findings in this and several other studies, absent or insecure land tenure detracts from soil conservation (Sklenicka et al., 2015).

Accordingly, the non-regenerative, non-controlling winegrowers in my research were more concerned with vine health than soil health. They felt powerless to change existing infrastructure, and financial viability as well as the cost of adoption, rather than long-term sustainability, were front of mind. And unfortunately, soil degradation happens primarily where farmers consider soil only as an economic asset (Sklenicka et al., 2015). My findings also showed that non-regenerative, non-controlling winegrowers would only adopt new practices if they had the existing skills and they seemed to lack access to training or experience-sharing.

In contrast, in my research, the regenerative, controlling owners knew how to adopt regenerative practices, didn't mind overcoming existing infrastructure, and simply had to be personally convinced about a practice to adopt it. They were more concerned with soil health than with vine health, and evoked ecological-economic equilibrium over financial viability. Other studies have found that ownership, length of residence and other types of place attachment to a human or non-human community positively affect disaster preparedness (Sasmita Mishra, Mazumdar, & Suar, 2010), which is important in light of soil health and the impending climate and biodiversity crises. For farmers, mitigating soil risk disasters such as erosion, compaction or exhaustion is paramount to ensuring sustainability.

Land is a long-term investment and Fraser (2004) found that ownership may be psychologically necessary for a farmer to be willing to invest in soil. For example, landowners may have access to soil stewardship incentives that non-owners do not have; some countries provide payments for ecosystem services, and the United Kingdom has even attempted to require landowners to provide a soil status report when selling land

(McNeill et al., 2018). In comparison to those who rent, farmers that own their own land have also been found to plant more perennials, grain and forage legumes (Fraser, 2004), actions that concord with soil regenerative practices such as agroforestry, cover crops, legume cover crops, and animal integration.

Sklenicka et al. (2015) found that a landowner's motivation relates less to short-term yields and is also tied to intrinsic value of the land, one that can be increased and passed on to successors (Sklenicka et al., 2015). Transmission within the family is privileged within the viticulture sector in central Europe including Switzerland, and indeed once parents or unmarried aunts and uncles reach a certain age – often 60 years or more - they tend to try to hand part or whole ownership over to their children rather than sell the vineyard (Head-König, 1998). Land ownership is the principal wealth of rural areas, and can garner social status and political influence (Norton, 2005), both of which can ease the adoption of innovative practices.

According to my findings, greater landlord involvement (where the landlord was not the winegrower) appeared related to adopting fewer regenerative practices. Therefore, for soil regeneration, where controlling ownership of a vineyard by a winegrower is not possible, landlord support for winegrowers adopting regenerative practices is. A recent study found that absentee landlords tend to offer few new social capital resources (such as networking) and knowledge for the winegrowing community (Aldecua et al., 2017). Yet Varble, Secchi and Druschke, (2016) conclude that building farmer-to-farmer relationships is paramount to environmental practice adoption, and that both owners and renters rely on personalized, interactive forums and field demonstrations facilitated by trusted individuals. Indeed, many of the barriers expressed by non-regenerative, non-controlling owner-winegrowers in this study could be overcome with landlord support. For example, infrastructure changes, being able to employ more people to overcome the capacity limits of having to implement a practice by oneself, providing time for access to training and networking, and freeing employees from a constant focus on cost, profit, and vine productivity are all within an owner's sphere of control.

Other soil regeneration incentives are possible in case of non-controlling ownership by winegrowers. Owners could give winegrower employees time and opportunities for attending field demonstrations or joining farmer-to-farmer discussion groups. A particularity in Vaud, Switzerland is that many tenure relationships are within the family, with either the parent(s) or sibling(s) as the owner(s) or co-owner(s) of the vineyard. In family-owned businesses, learning-by-doing is often more important than formal academic learning (Chirico, 2008). If the owner is not the winegrower, there may be no vehicle for knowledge transfer. Indeed, idiosyncratic knowledge, such as when to harvest grapes, is seen as essential to many agricultural practices (Pavel, 2013). Therefore, where a new generation of winegrowers in a family business would be asked to depart from traditional family practices, other sources of idiosyncratic knowledge, such as winegrower exchanges or demonstrations, would appear to be necessary. Also, where the winegrower is not the owner, the owner can motivate the winegrower to invest in soil regeneration by increasing tenure security (Sklenicka et al., 2015). This is because ambiguous or absent property rights can lead to short-termism and irresponsible resource use (Fraser, 2004). However, in terms of farmers active in soil regeneration, one cannot assume that even long-term leases can substitute for land ownership (Fraser, 2004).

In essence, winegrower land ownership may increase regenerative practice adoption and should be encouraged wherever possible, for their link with the soil is important. However, owners that are not the winegrowers can also encourage soil stewardship by empowering the winegrowers that work for them through strong tenure security as well as opportunities for training and farmer-to-farmer networking and discussion groups.

### H4: Empower Women Winegrowers to Adopt Regenerative Practices

My findings indicated that women winegrowers may need empowerment to adopt regenerative practices. The following section provides an overview of human capital factors that were important for women winegrowers, what biases may hinder women from adopting new practices, and measures such as winegrower clubs or bespoke advisory services that can strengthen risk-taking and practice adoption by women.

My research found that for women, competency in a practice was an important enabler whereas men just needed the practice to be interesting. Indeed, the interview results indicated that human capital, though not cultural capital as I had hypothesized, matters more for women than men winegrowers in adopting soil regenerative practices. Women felt that in order to adopt a new practice, they need to understand it and know how to apply it. For men, on the other hand, acquired knowledge about a practice seems to be less of an issue and taking a risk to try something depended simply on interest.

This difference in attitude toward human capital may have to do with historical differences between men and women in access to information. There is a large body of research that shows that men have greater access to extension services (otherwise known as agricultural advisory services), which can take the form of field visits, technical advice at organized meetings, visits to demonstration farms, or farmer field schools (Quisumbing et al., 2014). These differences in access can include outright access, frequency of access, or gendered aspects of services provisions (Quisumbing et al., 2014). Women winegrowers may therefore be reticent to adopt new practices because they may not have access to human capital in the form of knowledge-building extension services, whereas for men this may be less the case.

Technical innovation has driven agricultural innovation for the past decades. For adopting new agricultural technology in developed countries, studies show that in official policy documents women are implicitly indicated as lacking technical skills, playing into the perception that technical innovation is difficult for women and belongs to the realm of men (Pecis, 2016). This perception and delegitimization may be especially challenging for women in the male-dominated Swiss winegrower world. With advances in information and technology in the agricultural sector, mechanization especially tends to exclude women from its use and overlook womens' needs and constraints (Beuchelt, 2016).

Such conscious or unconscious biases raise important issues for women accessing and maintaining a livelihood (here a profitable winemaking business), because equity of access relates to control of the natural, manufactured, financial, human and social capital needed for growing grapes, making and marketing wine (Beuchelt, 2016). In my research, women winegrowers seemed concerned about their personal ability to acquire knowledge about new practices, while men expressed simply waiting for someone to show them something “interesting”. Women tend to have to prove themselves before they can take on a challenge such as a new practice, whereas men are generally not asked to prove themselves, and are rather evaluated on their potential to do something. In leadership for example, a woman’s potential tends to be overlooked when ranked against men, and women are expected to demonstrate higher past performance (including acquired skills or knowledge) (Player, Randsley de Moura, Leite, Abrams, & Tresh, 2019). Relevant, therefore, is that the men in my research expressed confidence in their potential to adopt soil regenerative practices, even if they were not (necessarily) willing to change their ways. Women, conversely, were more willing to adopt new practices (for willingness to change their ways was not evoked), but felt they had to prove their knowledge and skills yet lacked a personalized route to acquiring these.

Providing women with access to information, educational or exchange platforms may therefore be one key to regenerative practice adoption. Women’s decision-making power in agriculture is highly influenced by their education, perception of land rights equality, and access to advisory services (Zhllima, Xhoxhi, & Imami, 2020). However, their access to advisory services in agriculture is very limited (Zhllima et al., 2020). In many places, agricultural extension and advisory services also tend to be male-biased, both in terms of delivery and content (Lecoutere, Spielman, & Van Campenhout, 2019). Empowering women in agriculture by increasing their knowledge, their independent decision-making, and their adoption of new practices therefore depends on information being provided directly to women, and preferably including women as role models (Lecoutere et al., 2019). Indeed, designing bespoke platforms to provide agricultural information to women farmers can help them increase their knowledge of agricultural practices and take more risks, even if ultimate adoption may depend on other factors, including access to financial capital (Raghunathan, Kannan, & Quisumbing, 2019).

To conclude, women winegrowers may require empowerment to adopt regenerative practices. Providing women farmers with bespoke access to farmer-to-farmer information networks such as winegrower clubs, or with direct and tailored advisory services, preferably by women, can strengthen adoption. Women in agriculture may also require better rewards or reinforcements for taking risks, such as adopting new and “interesting” practices even when they don’t have all the knowledge and skills required. Ultimately, what matters is making opportunities and pathways to agricultural innovation such as soil regenerative practices more equitable and gender responsive (Beuchelt, 2016).

### H5: Overcoming the Hardest-to-Adopt Practices

I found in this study that agroforestry, animal integration, redesigning the system at the landscape level, but also low traffic were the hardest practices for winegrowers to adopt for perceived fear of decreased vine productivity, need for additional vineyard resources, or lack of time. In this section, I go into more detail on my findings, and explain how these perceptions may be unfounded. I also provide practical tips, such as further research and co-production forums, for overcoming the barriers to adopting these practices.

In my findings, agroforestry was difficult for winegrowers to adopt because of fear of decreased vine productivity. A recent study by Sereky et al. (2016) came to similar conclusions that farmers in Switzerland were generally convinced that agroforestry is not productive compared to monoculture, and were resistant to adopting agroforestry for fear of appearing unproductive vis-à-vis their peers.

However, this fear of agroforestry reducing crop productivity is unfounded. It is true that up until recently, research was lacking on the potential competitive interactions between trees and adjacent crops in terms of limiting water, nutrient and light (Asbjornsen et al., 2014). However, according to a study on mixed perennial–annual agricultural systems in the Midwestern USA, it is now known that including trees and hedges in and around fields can improve biological control of crop pests that would otherwise lower productivity (Asbjornsen et al., 2014). Moreover, diversifying perennial plant communities within a cropping system can increase carbon storage, provide habitat for organisms that feed on crop pests, provide pollination services that increase productivity, mitigate climate change and contribute to soil quality which is key for sustainable crop productivity (Asbjornsen et al., 2014). Agroforestry systems in Europe were more productive than monocultures by 36-100% (Lehmann et al., 2020). Finally, integrating trees in cropland has further benefits such as improved hydrologic function, increased biodiversity, and especially broadleaf trees can contribute to more pronounced increases in soil organic C stocks relative to pastures or grasslands (Asbjornsen et al., 2014).

Apparently, however, much recent research on agroforestry is not yet available to farmers (Sereke et al., 2016). The majority of farmers have not been provided with findings such as the role of agroforestry in climate regulation, soil and groundwater protection, nor with evidence from a Sereke et al. (2016) study on arable crops in

Switzerland that agroforestry can be more productive and profitable than monocropping alone.

As one winegrower interviewed in this study pointed out, the fight between the forest and the vineyards is a long one, as evidenced by the sharp line that is drawn in some parts of Vaud between the vines going up the mountain over once deforested land and the forest encroaching on vineyards toward the lake. The deforestation of Europe to provide space for agriculture has, for millennia, gone on under the banner of progress (Gross, 2014). Collective consciousness has only recently become aware that forests provide a wide range of ecosystem services (Gross, 2014). Recent notions such as climate-smart agriculture and agroecology are helping farmers transition from monoculture and reliance on chemical inputs to an integrated farming approach including agroforestry by reintroducing biological complexity, including plant diversity, perennial cover and the presence of trees (Food and Agriculture Organization of the United Nations, 2017).

However, greater translation of scientific knowledge into practical farmer and winegrower circles, for example through multi-stakeholder collaboration platforms or other forums for co-producing shared visions and solutions, may help socialize the benefits of agroforestry (Sereke et al., 2016). Such platforms can help farmers sympathize with consumers, environmentalists, and politicians and overcome the perception that adopting agroforestry could have a negative impact on their reputation vis-à-vis other farmers (Sereke et al., 2016).

Animal integration was seen as difficult to adopt because more resources (especially employees) were required. Indeed, the coordination and logistic costs, as well as the additional skills needed for animal integration, have been found to be a barrier for winegrowers (Niles, Garrett, & Walsh, 2017). However, a recent study on sheep integration in viticulture demonstrates that the practice has the potential to significantly reduce the use of herbicides and tractor mowing, thus leading to lower labor costs and higher profits (Niles et al., 2017). Most winegrowers that integrate animals do so only seasonally, yet it has been found that farmers that integrate sheep year-round have lower labor and input costs as sheep can save them from having to manually or mechanically pluck weeds from the vines (Niles et al., 2017).

Historically, crop-livestock farming was mainstream, and animals were essential to recycling nutrients in the farming system. For eight millennia, farm systems in Europe have been mixed. However, since the 18th century, livestock has been gradually separated from crops with the availability of synthetic fertilizers and through agricultural specialization (Schut et al., 2021), and animals have been disassociated from winegrowing. Crop farmers – including winegrowers - have lost the skillsets to manage both livestock and cropping systems (Niles et al., 2017).

A better understanding of the benefits of animal integration may help farmers balance perceived resource costs and constraints. One winegrower interviewed in my study scoffed at animal integration, saying it was done primarily as a tourist attraction. However, sheep integration in viticulture can for example provide economic, environmental, labor and production benefits (Niles et al., 2017).

To encourage animal integration, Niles, Garrett, & Walsh (2017) suggest that winegrowing associations could play a role in providing training in re-integrating crops and animals, and a certification scheme might help reward winegrowers through added marketing value (Niles et al., 2017). More research on the integration of different types of animals in mixed animal-cropping systems could also be beneficially. For example, sheep integration remains largely unexplored because most integrated crop-livestock systems research focusses on cattle (Niles et al., 2017). Finally, Schut et al. (2021) suggests that policy encourage a mix of farm types within close proximity, together with participatory design processes such that practices can be evaluated and implemented at the landscape scale.

For redesigning the system at the landscape level, lack of time was the biggest barrier my study found. Indeed, redesigning the system at the landscape scale requires cooperation with neighbors or political authorities. Yet French-speaking Switzerland, including Vaud, scores very high on the individualism spectrum ("Switzerland Country Comparison," n.d.). My study found that some larger winegrowers and some non-regenerative, non-controlling owners expressed a preference for practices that they can implement on their own, and even some regenerative, controlling winegrowers preferred practices where they don't have to count on others. Some Swiss winegrowers may therefore not be open to cooperation. However, this lack of cooperation may not be serving them, for in other politicized, landscape-related (potential) conflict issues, ex-ante cooperation schemes are considered far more cost effective and time efficient than ex-post compensation and insurance schemes that require payments or time to solve after an incident occurs (Leslie, Brooks, Jayasinghe, & Koopmans, 2019). And soil health may not be recuperable ex post, at least not on human timescales.

A particularity in Vaud is that redesigning the system at the landscape scale may go against the cultural heritage of legally protected conservation areas, such as the

Lavaux vineyards that have been classified for preservation in their present landscaped state by UNESCO. However, cultural heritage sites need to be considered as dynamic and changing landscapes if they are to be climate resilient (Shirvani Dastgerdi, Sargolini, & Pierantoni, 2019). Therefore, they should be evaluated and adapted by involving a wide range of stakeholders, knowledge exchange across a wide range of stakeholders, including heritage management, trans-disciplinary researchers, and community members such as farmers (Shirvani Dastgerdi et al., 2019).

Collaboration between farmers and soil protection actors at the local, regional and national levels is traditionally weak in Switzerland, and there are few forums for sharing best practices and co-creating knowledge and strategies (Schneider, Fry, Ledermann, & Rist, 2009). Moreover, when farmers are involved, someone is typically transferring knowledge to them top-down, implying hierarchy and power relations, and contributing to lack of trust (Schneider et al., 2009). In traditional knowledge exchange, farmer expertise, which is often tacit knowledge, is often neglected, as is a farmer’s contribution to the conversation (Triste, Debruyne, Vandenabeele, Marchand, & Lauwers, 2018). This lack of consideration and inclusion may be one reason why certain winegrowers may prefer to work alone rather than collaborating. Therefore, creating spaces for social learning processes that encourage co-creation rather than the usual top-down knowledge transfer is essential for building trust, fighting siloed behavior, and adopting new practices (Schneider et al., 2009). With the right enabling conditions for dialogue such as inclusion and levelling the playing field, winegrowers might even take the time to collaborate.

To summarize, to socialize new practices such as agroforestry, greater research solution co-production between farmers and scientists is needed. Practices such as animal integration may also require research on the integration of different types of animals (not just cattle), and co-production forums to encourage ways to move from monoculture to mixed farming or encourage a mix of farm types in close proximity (landscape-scale solutions). Because of the potential spillovers of these practices into the neighboring landscape, and to achieve landscape-scale visions and solutions for a sustainable future, winegrowers may need encouragement to collaborate with local farmers in close proximity or local political authorities. However, the hierarchies and power dynamics in co-production forums must be flattened for bottom-up innovation and for farmers to feel respected and included, for co-production requires that scientific knowledge not be privileged over farmers' knowledge (Schneider et al., 2009).

### H6: Regenerative Winegrowers' Intrinsic Motivation and Focus

I found that for regenerative and non-regenerative winegrowers, social capital was just as important as human, natural and financial capital, whereas manufactured capital was the least mentioned enabler (Figure 18). What distinguished them from non-regenerative winegrowers was caring for soil life (natural capital) and intrinsic motivation with a view to long-term ecological-economic equilibrium (financial capital). Nourishing local ancestral practices and beliefs can help winegrowers value all Life on Earth, including soil and human life. Social influence and sovereignty on decision-making can strengthen intrinsic motivation.

The way that a community views the world has an influence on how soil is valued and cared for. The biodynamic and organic winegrower communities were all regenerative and motivated by a living soil and biodiversity. Biodynamic practices are inherently organic, and organic farming practices use neither synthetic fertilizers nor synthetic pesticides, and rather aim to close nutrient cycles that rely heavily on healthy microbial communities to break down organic matter and return nutrients to crops and other living organisms  (Lori, Symnaczik, Mäder, Deyn, & Gattinger, 2017). This positive impact on soil microbial life of organic practices may be of vital importance in the context of climate change, for there is evidence that organic systems outperform conventional systems in terms of yield in more extreme weather conditions  (Lori, Symnaczik, Mäder, Deyn, & Gattinger, 2017).

A growing body of research and practice is beginning to look at human-soil community relationships in terms of reciprocity and caring for one another (Pigott, 2020). According to Pigott (2020), “care is becoming a useful concept for thinking with (rather than only about) soils, and for considering the kinds of agencies and communities (humans and more-than-human) that sustain life in myriad ways” ( p. 2). For biodynamic winegrowers, in particular, soil is not an inert matter and the communities alive in soil have energy and can regenerate life, better than through artificial, industrial-agricultural methods (Pigott, 2020). Indeed, the way people view the world – their psychological schemas or worldviews – drives their beliefs and behaviors (Blume, 2020). There are multiple ways of viewing the world – some more spiritual or caring – including indigenous ways that have largely been ignored by Western science until recently.

Spirituality has been largely left aside in industrial, Western agriculture, yet spirituality can reprogram how soils are conceptualized and cared for (Pigott, 2020). Moreover, in many indigenous cultures – which one could liken to local communities - spirituality underpins intrinsic motivation (Ohajunwa & Mji, 2018). According to Blume (2020), local communities or "indigenous people typically define themselves by their relationship to the Earth", and especially indigenous people have a special reciprocal relationship with soil and non-human living beings (Blume, 2020, p. 4). Indigenous worldviews point to Mother Earth as the basis of all creation, a story that typically clashes with the creation stories of Western civilizations that have gone to great lengths to colonize and remove indigenous populations and ways of thinking (Blume, 2020). Despite these erasure efforts, there is still much knowledge that can be gathered and learned for soil and human health and wellbeing from indigenous community elders, cultural beliefs and stories (Blume, 2020). One example in Switzerland is biodynamic winegrowing, which bridges the spiritual and the material world, though often leads to people considering biodynamic winegrowing more of a belief than a practice (Castellini, Mauracher, & Troiano, 2017). However, this study found biodynamic winegrowers firmly in the regenerative camp (Figure 5).

In terms of the relationship between financial capital and social capital, the question of intrinsic versus extrinsic motivation is an interesting one. According to Edinger-Schons et al. (2018), intrinsic motivation can be defined as a "genuine desire to benefit humankind and the planet, construed more broadly as altruism", whereas extrinsic motivation means "material incentives, such as material savings, and/or image incentives, such as the approval of relevant others" (Edinger-Schons, Sipilä, Sen, Mende, &

Wieseke, 2018, p. 644). Economists have recently put forth that altruistic, pro-social behavior creates positive feedback loops; that is, altruistic behavior triggers an increase in the return on such prosocial behavior, thus allowing the accumulation of altruistic capital to further dispense (Ashraf & Bandiera, 2017). Meanwhile, providing financial incentives can backfire and even diminish altruistic behavior (Ashraf & Bandiera, 2017). Experimental evidence shows that extrinsic motivation (such as consumer demand) can conflict with an individual's intrinsic motivation (an individual might want to do something but be deterred by the fear of being perceived by peers as wanting to do it just to please the consumer) (Benabou & Tirole, 2003). One study found that that people are intrinsically motivated to adopt pro-environmental practices because contributing altruistically to the greater good makes them feel good about themselves (Steg, 2016).

But what about those lacking intrinsic motivation, that will only adopt a practice "because the tourists ask for it"? Strengthening typical extrinsic appeals (consumer preferences or tourist demand, for example), can unfortunately expel people's own intrinsic reasons to behave pro-environmentally (Edinger-Schons et al., 2018). Research also shows that mixing extrinsic appeal with intrinsic appeal decreases, rather than increases, a purchase or adoption (Edinger-Schons et al., 2018). Therefore, appeals such as "how soil regeneration can save you money" would likely backfire, because they appeal to both intrinsic motivation to regenerate soil for the benefit of nature and people, and to an extrinsic, financial motive.

Instead, to help bring out people's intrinsic pro-environmental motivation, social influence strategies can be powerful, for example by providing farmers with information about consumer preferences or about the behavior of other farmers and especially leaders in their network, with face-to-face strategies being the most effective (Steg, 2016). Fellow farmer advocates will be most compelling when they have adopted a practice themselves, and making their commitment public can increase the impact of their social influence (White, Hardisty, & Habib, 2019). Indeed, social influence is one of the most effective ways to influence pro-environmental consumer behavior as well, and telling consumers that others are buying environmentally-friendly products has been shown to lead to a 65% increase in sustainable purchases (White et al., 2019). Therefore, telling wine consumers that others are buying products from regenerative farms could lead to more demand for regenerative wine, which in turn could extrinsically motivate non-regenerative winegrowers to adopt more regenerative practices.

In addition, appealing to spiritual indigenous or local community values, and facilitating connectedness to the self, others, soil, plants and animals, may be a powerful way to drive intrinsic motivation and heal severed relationships between people, soil and other living beings (Blume, 2020). However, programs or policies introduced for indigenous or local farmers need to be mindful of the community values and context, or else intrinsic demotivation can occur because people are being forced to do what has no value to them (Ohajunwa & Mji, 2018). Many of the winegrowers in this study emphasized the important of independence as an enabler for adopting regenerative practices (Figure 11), and indeed this is an important point, for intrinsic motivation to think or behave in a certain way requires autonomy and sovereignty. Moreover, autonomy and independence can apply not only to individuals, but also to a collective (Ohajunwa & Mji, 2018). Communities – including agricultural communities - can have a powerful, cultural ‘collective self’, which is grounded in relations with others and sometimes in relations with spirituality (Ohajunwa & Mji, 2018).

In brief, caring for soil life and intrinsic motivation characterize regenerative winegrowers. Encouraging learning local ancestral practices, beliefs, or stories, for example by engaging with community elders or those that carry on spiritual traditions such as biodynamic winegrowing, may help to nourish worldviews that value soil life and caring for human and non-human beings, which is key to regenerative agriculture. Moreover, intrinsic motivation is important for regenerative practice adoption. Social influence and independence/sovereignty to make decisions can strengthen intrinsic motivation.

## Research, Policy and Practice Implications

This study has found that worldwide, practicing mixed farming, and combining regenerative practices rather than practicing monoculture can help farmers sequester soil organic C, which in turn can mitigate the effects of climate change, regenerate biodiversity, ensure long-term soil productivity, and secure human health and wellbeing. Moreover, it found that viticulture is a particularly favorable crop to lead the way for regenerative agriculture. However, smaller vineyards need information on soil regenerative practices and social reinforcement to adopt them. It is important, if possible, for winegrowers to be controlling owners for soil stewardship. Women need ways need ways to feel confident in their regenerative practice knowledge and skills. Research and solution co-production is needed to overcome the practices that are perceived as hardest to adopt. Finally, participatory planning processes can provide social reinforcement to spark the intrinsic motivation and care for soil life that characterizes regenerative winegrowers.

How then, can different societal actors play a part in soil regeneration? Based on the findings from this study, what can winegrowers and other farmers do differently? How might natural and social science researchers go forth? What are the next steps for policymakers, consumers and influencers?

## Winegrowers and Other Farmers

Regenerative farmers including winegrowers can lead by example, taking after farmers like Gabe Brown in the United States, who testified before Congress in 2021 about the advantages of regenerative agriculture to sequester soil organic C and increase farmer profitability (US House of Representatives, 2021). This study has shown that for intrinsic motivation toward long-term ecological-economic outcomes, it is important for winegrowers to collaborate with others. Indeed, working together with others on a challenge, especially when the challenge connects to personal values and identity, broadly increases intrinsic motivation (Carr & Walton, 2014). Moreover, access to information and networks was the principal barrier found in this study for smaller winegrowers, who otherwise have the agility to regenerative practices. Collaboration with other stakeholders including researchers, policymakers and other farmers encourages information flow social reinforcement. Indeed, social norms are reinforced over time through collaboration (Rust et al., 2020). Such collaboration that includes women farmers/winegrowers or that is between women winegrowers can be especially beneficial for women that require the confidence in their knowledge to adopt new practices.

Participatory processes can help winegrowers obtain access to information and social reinforcement for other practices that are perceived as difficult to adopt too, such as animal integration, agroforestry, and low traffic. Moreover, such participatory processes can be the building blocks for regenerative communities and help to reinforce what Ohajunwa & Mji (2018) call the cultural 'collective self' and nurture intrinsic motivation and a spiritual connection with soil life. Aside from joining or creating knowledge-sharing groups, smaller winegrowers can also look to collaborating with others to avoid investing in too much locked-in infrastructure or machinery that could make them less agile in a rapidly evolving environment.

### Researchers

In the face of climate change and biodiversity loss, it is increasingly important that researchers including ecologists also engage with stakeholders and in public dialogue (Parrott, 2017). Researchers, especially interdisciplinary researchers that can bridge the natural and social sciences, can help translate scientific knowledge and socialize new practices into practical farmer and winegrower circles, for example through forums for co-producing shared visions and solutions. One way to co-produce landscape-scale solutions can be to provide and fund platforms for local farmers, policymakers at different levels, and researchers to engage together in flat-hierarchy situations where farmers' knowledge is valued on par with scientific knowledge (Schneider et al., 2009). Researchers can also encourage further research on regenerative practices, such as on the integration of other animals besides cattle. And, especially women researchers can help set up direct and tailored advisory services for women farmers and winegrowers.

### Policymakers

Regenerative agriculture essentially aims to be a closed-nutrient system, regenerating all the life it requires within a community of humans and non-humans. Giving communities – and especially winegrower communities that value independence - autonomy, independence and sovereignty to make their own decisions is therefore key to successful regenerative agriculture. Top-down policymaking is not effective or sustainable in this context (Parrott, 2017), and policymakers of the future will need to collaborate and engage in co-creation with farmers and other stakeholders for sustainability. Participatory approaches to rural regeneration and regenerative planning processes in Europe are only just being put in place, relying on a diversity of actors to improve the quality and legitimacy of decision making while “simultaneously generating additional benefits, such as social learning, social capital and empowerment” (de Luca et al., 2021, p. 2). Participatory processes can ensure that smaller vineyards with more agility to adopt regenerative practices have a voice. They can ensure that legislation and funding enable ownership by winegrowers themselves who are motivated to steward the land. When women winegrowers’ voices are included, services and learning opportunities can be better tailored to their needs for soil regeneration. Finally, participatory processes can move forward effective practices that winegrowers perceive as difficult to adopt and may tackle last. For example, encouraging landscape-management approaches including policymakers, farmers, consumers and others can be very effective for long-term agricultural impact (WWF, 2021). Moreover, fiscal policy and inheritance laws can enable winegrower and other farmer ownership or tenure where possible to preserve a connection to the soil. Finally, policymakers can provide, through subsidies or certification for example, a way for small winegrowers to market the soil regenerative practices they adopt.

## Consumers and Influencers

As the urgency of climate change and biodiversity decline is becoming increasingly apparent, people are becoming more conscious of what they consume, and sourcing their provisions increasingly locally. By looking past social norms of what conventionally makes a great wine, and diving beyond wine bottle labels to see, feel, smell and get that "taste of the Earth" that their local terroir has to offer, consumers can drive demand for regenerative agriculture. The concept and benefits of regenerative agriculture are gaining traction, and must be perceived as becoming mainstream rather than marginal. Public figures and celebrities, such as Woody Allen in the film Kiss the Ground (Tickell, 2020), can help strengthen the public image of regenerative agriculture by speaking or acting in favor of it.

Indeed, in an increasingly systemic and interconnected world, farmers, researchers, policymakers and consumers will need to collaborate. Overcoming barriers to soil regenerative practice adoption in Switzerland and elsewhere around the world requires creative transformative pathways and collaboration, through concepts such as soil stewardship, which requires a collection of stakeholders united around care, knowledge and agency (Plummer, Baird, Farhad, & Witkowski, 2020). Soil stewards of the future will need to engage in discovering and co-developing solutions with a "multiplicity of actors (land owners, land tenure holders, etc.) and levels of governance (from municipal to state/provincial to federal), many of them overlapping on the same parts of the landscape" (Parrott, 2017, p. 1006). Co-development will be important not only for regenerative winegrowing in Switzerland, but also for regenerative agriculture generally around the world. A wide diversity of societal stakeholders, such as landowners, can and should be included in multi-stakeholder co-creation of the future. Such forums can encourage landowners to strengthen tenure security or to support tenant-farmer training and farmer-to-farmer networking and discussion groups for soil stewardship. Engaging in co-creation can demonstrate that independent/sovereign winegrower decision-making can strengthen intrinsic motivation to care for soil health. Participatory processes can help regenerative unique, collective cultural and natural heritage including values, beliefs, knowledge, and traditions that once existed in now degraded landscapes (de Luca et al., 2021). Healthy soil and people are the basis of that cultural and natural heritage.

## Research Limitations

I note a few methodological caveats to this research.

### Limits to Quantifying Soil Organic C (H1)

In quantifying soil C for the different regenerative practices, my review of definitions and my taxonomy focused mainly on English-speaking research articles. However, I recognize that many concepts and studies may have been elaborated in other languages and may not be well presented here.

Another important limitation was that in many studies, the research design of the study masked the start of the experiment (baseline). This shortcoming made it impossible to determine whether a measured difference in soil organic C between two treatments was caused by the practice or not, and I was therefore not able to include many of the studies I evaluated. It would be helpful for future experimental research to always measure a baseline.

Moreover, most of the studies sampled measured carbon sequestration at a depth of around 20-30 centimeters, which doesn’t consider a substantial part of soil organic C which can be sequestered in deeper soil horizons. Under certain management conditions with deep-rooting plants, 64% of total soil organic C stocks can lie at depths of 20-80 centimeters (Gattinger et al., 2012). Soil organic C is rarely measured deeper than 30 centimeters, even if it is known that carbon is better protected from loss in the subsoil (Tautges et al., 2019). However, measuring carbon to a depth of two meters allows much greater soil carbon sequestration capacity than surface soil sampling can show (Tautges et al., 2019).

It is also important to note that a relatively small number of carbon sequestration samples were found for all practices except for non-chemical fertilizer, and that in many cases a lack of study samples mean that I often had to use proxies, such as an orchard or permanent crop instead of a vineyard, a forest versus a vineyard for agroforestry, or manure application for measuring the effects of animal integration. Therefore, the carbon sequestration figures would likely require further samples from long-term studies done specifically in vineyards and with the specific practices for verification.

Finally, no data samples were found for the practices of low traffic and redesigning the system at the landscape level, so their contribution to carbon sequestration in vineyards is unknown.

### Limits to Uncovering Winegrower Barriers and Enablers (H2-H6)

This study constituted exploratory research about winegrowers in the Canton of Vaud, Switzerland. The results are therefore not necessarily representative of all winegrowers in Switzerland, nor all winegrower or farmers in the rest of the world.

The part of the study based on winegrower interviews was qualitative in nature. Although 12 to 20 participants are recommended in interview studies, where saturation tends to occur within 12 interviews (Sim et al., 2018), I am nevertheless reporting the opinions of a small proportion of winegrowers, so care should be taken with overgeneralization of results.

Moreover, qualitative research likely includes respondent biases (Quisumbing et al., 2014). Even though winegrowers were not identified personally, the reliability of data collected is subject to the limits of their willingness to share enablers and barriers openly.

Finally, winegrower perceptions of enablers or barriers were subject to their knowledge of the different practices. For example, some practices were new or unfamiliar to some winegrowers and not understanding the full implications of their application made it difficult for them to assess to what extent they may have already adopted them or not. Agroforestry, for instance, is a relatively innovative practice and for many it was hard to determine whether a few trees or hedges growing in or on land alongside their vineyard counted as having adopted agroforestry, intentionally or not.

## Conclusions

In conclusion, current conventional soil management practices must evolve for climate change to be addressed and for nature, including people, to thrive. Adopting soil regenerative practices has many benefits, including soil organic C sequestration, that are essential to reaching the European Economic Area's goal of increasing healthy soils by 100% by 2030.

The agricultural sector, and notably viticulture because of its greater innovation and carbon sequestration potential, have an essential role to play in transforming the food system that has been responsible for the degradation of soil in past decades. Adopting soil regenerative practices in agriculture can turn agriculture from one of the largest contributors of anthropogenic greenhouse gas emissions into a secure ecosystem provider of food that builds soil organic matter, restores degraded biodiversity and human health, and reverses climate change.

Overcoming the barriers to adopting these practices is therefore vital. An important enabler is cooperation, for example through intrinsically-motivated soil stewards that engage in co-developing ways forward with a multiplicity of community stakeholders. Knowledge-sharing and co-creation groups need to flatten hierarchies and power dynamics, and be inclusive of women's and local farmers' needs and knowledge. Policy can also be co-created to encourage new practices and land ownership/stewardship and decision sovereignty by smallholder farmers.

However, in order to regenerate soil and human health, winegrowers and other farmers, researchers, policymakers, consumers and influencers all need to collaborate at the landscape level and without impeding on local farmer and winegrower sovereignty and independence. Research, practice, and policy must be able to converse, and all stakeholders need to converge around care, knowledge, and agency to consider soil for its full ecosystem service, cultural and intrinsic values.

Only then will we have healthy, living soil as the basis for essential ecosystem services, including human health and food from agriculture. And only then will Rodale’s vision become a reality: a regenerative culture, where agriculture is embedded in rituals, meals, ceremonies, singing, storytelling and music in a caring and meaningful community.

# Appendix 1

## Description of the Nine Regenerative Practices Identified for Viticulture

1. The first of the nine regenerative practices for viticulture, agroforestry**,** involves integrating and managing trees within and around vineyard (Bourgade et al., 2020). It is described by the Food and Agriculture Organization (FAO) as "a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels" (Larbodière et al., 2020, p. 57). It combines a number of ecosystem and social services, including soil and biodiversity improvements, climate mitigation, carbon sequestration, wood for artisanal purposes, and improved vineyard and landscape image (Bourgade et al., 2020). Agroforestry within a parcel of land principally permits below and above-ground carbon sequestration in the in form of woody biomass of trees or bushes. However, it also increases soil carbon storage via net primary production, through the return of tree litter to the earth, root and rhizosphere decomposition, and non-tillage of areas around woody plants (Chenu et al., 2014).
2. The second practice is the use of a cover crop (non-legume), which applied to vineyard middle rows is one of the most recommended practices to improve vineyard sustainability, though currently it is not widely applied (Novara et al., 2020). In vineyards, it has been shown to increase soil organic C (Nistor et al., 2018), diminish soil erosion and nutrient loss, increase soil fertility and structure, regulate vine growth

and yield quality, improve beneficial soil microbial diversity, and attract beneficial insects (Novara et al., 2020). Perennial systems such as vineyards are able to support year-round cover crops that are typically mowed or returned to the soil after growing them (Jackson et al., 2009). The presence of vegetation in vineyard alleys can contribute to the buildup of soil organic matter (Scandellari et al., 2016). Cover crops can regulate vine growth by improving water penetration and soil fertility, and may help with pest management (Zhu-Barker et al., 2018).

3. The third practice is the use of a legume cover crop, which can add nitrogen to the soil and reduce soil nutrient leaching, and therefore decrease the need for chemical fertilizers (Nistor et al., 2018). Nitrogen is required for plant growth, and needs to be in mineral form to be absorbed by plants (Pisciotta et al., 2021). In vineyards, the use of a nitrogen-fixing legume cover crop has been shown to increase mineral nitrogen available after the first year, provided that prunings are left on the ground and microorganisms are allowed to thrive (Pisciotta et al., 2021). The pruning trimmings and microorganisms are required to transform nitrogen into mineral nitrates for root uptake (Pisciotta et al., 2021). Only once microbes have converted nitrogen from organic to mineral do grapevines have access to native soil nitrogen (Nistor et al., 2018). Moreover, use of a nitrogen-fixing legume cover crop instead of high nitrogen fertilizer inputs may reduce the risk of nitrate pollution in groundwater (Pisciotta et al., 2021). When legumes are included in cover crop and no-tillage conditions, soil organic C increases significantly (Garrett et al., 2020).
4. Fourth, animal integration or mixed crop-animal farming involves combining crop and animal systems (Garrett et al., 2020). Such mixed systems were common

historically and have now largely disappeared. However, animal integration closes the loop in nutrient and energy cycles, and returning animals to cropland can reduce the negative externalities of separating from animal feeding operations while upholding profitability and yields. (Garrett et al., 2020) Integrating ruminants into regeneratively managed ecosystems to graze grasses or other cover/rotational crops can increase soil organic C, improve soil functioning and enhance biodiversity and wildlife habitat, and integrating ruminants consuming only grazed forages under appropriate management can result in more C sequestration than emissions (Teague et al., 2016). Manure from ruminants can increase soil C contents directly from the added carbon in manure itself, but also by improving the physical attributes and nutrient availability of the soil, thereby increasing plant productivity and residue carbon inputs (Paustian, Larson, Kent, Marx, & Swan, 2019). Animal integration is a promising practice for soil quality, the environment, resource efficiency, nutrient recycling, landscape diversity, and human health (Oenema et al., 2017).

5. A fifth practice for viticulture is low traffic. Low traffic is a principle of soil management aimed at protecting soils by reducing heavy traffic loads and high passing frequency of farm machinery that causes damage to soil structure, risking runoff and erosion upland and waterlogging and ponding in lowlands (Giraldez Cervera et al., 2017), and restricting root colonization and reducing soil organism communities (Champart, Guilpart, Mérot, Capillon, & Gary, 2013). In perennial crops such as grapevines, mechanization poses a considerable risk to soil degradation (Champart et al., 2013). Farm mechanization to increase productivity is one of the main drivers of subsoil compaction, a serious threat to soil structure and health at

deep layers that is very difficult to remediate (Giraldez Cervera et al., 2017). Risk of soil structure degradation due to mechanization may increase when converting to organic viticulture, as herbicides and pesticides are replaced with mechanical weed control and other treatments (Champart et al., 2013). Reducing tillage and tractor passes is one of the most efficient practices for lowering greenhouse gas emissions in vineyards, though it takes many years before the resulting soil organic C changes can be detected (Nistor et al., 2018). In vineyards, damage can be mitigated by avoiding traffic when soil is moist, using low-pressure tires and reducing traffic (human or machine) by combining treatments, for example (Champart et al., 2013). Reducing compaction also reduces the need for tillage (Paustian et al., 2019).

6. The exclusive use of non-chemical fertilizer is a sixth regenerative practice. Regenerative farmers reduce or eliminate the use of chemical inputs such as synthetic fertilizer (Gosnell et al., 2019). Instead, non-chemical (organic) fertilizers may be used, containing a wealth of organic material and nutrients that feed soil organisms and increase soil organic matter, whereas chemical (synthetic) fertilizer primarily benefits plants and can have various negative effects on soil, such as decreasing its fertility by increasing its salinity and acidity (Larbodière et al., 2020). Fertilization is widely used worldwide to improve soil fertility, but chemical fertilizer has been shown to have a negative effect on soil quality and soil microbial community structure in vineyards, decreasing bacterial abundance and diversity in the longer term (Wu et al., 2020). Applying chemical fertilizer tends to improve crop yield in the short term, but it barely maintains and even decreases soil organic C in the longer term, whereas non-chemical fertilizer can improve both crop yield and soil organic C

sequestration (Li et al., 2017). An example of how non-chemical fertilizer can contribute to soil carbon sequestration is by preserving bacteria that regulate metabolic pathways to soil carbon inputs and losses (Ahmed, Odelade, & Babalola, 2018).

7. A seventh regenerative practice for viticulture is non-chemical pest management. Regenerative farmers also reduce or eliminate the use of chemical inputs such as herbicides, and pesticides (Gosnell et al., 2019). In regenerative farming, soil is seen as a biological system of underground life that matters rather than as a chemical reservoir where life must be killed and replaced (Gosnell et al., 2019). Soil organic C formation depends on microorganism biodiversity, and chemical pest control can impact the populations of bacteria, nematodes, protists and fungi, thus destabilising the system and carbon sequestration (Pellerin et al., 2019). Non-chemical pest control can therefore increase soil microbial biomass carbon and mycorrhizal colonization (Meena et al., 2020).
8. The eighth regenerative practice is no-tillage. ‘No-till’ can be defined as a complete elimination of soil ploughing in agricultural systems (Beach et al., 2018).  No- or reduced tillage is a soil management practice that contributes to environmental preservation and sustainable agricultural production, and is often cited as increasing soil organic C sequestration (Su, Gabrielle, & Makowski, 2021). One issue is determining the tolerance level for tillage – for example, is it enough to till less frequently or more shallowly than the norm, and is ploughing every few years when cultures are replaced considered no-till? (Beach et al., 2018). Since the advent of tillage-based farming, most agricultural soils have lost 30% to 75% of their soil

organic C, and industrial agriculture has exacerbated these losses (Teague et al., 2016). No- or reduced tillage can increase soil organic matter, reduce erosion, increase water quality, promote water retention in the soil, and increase soil biodiversity (Larbodière et al., 2020). Reduced or no-tillage also preserves soil organic matter from mineralization (Scandellari et al., 2016). In terms of carbon sequestration, prevention of erosion may be an important effect of no-tillage because the fate of soil organic C transported, redistributed and deposited by erosional processes is a subject of intense debate (R. Lal, 2005).

9. A ninth practice is redesigning the system at the landscape level. Sometimes called ‘vinecology’ (Viers et al., 2013), a landscape-level approach is a holistic, integrated, systems-level framework that transcends traditional management boundaries (including overstepping the boundaries of the vineyard or what is customarily considered to pertain to winegrowing) and aims to balance competing demands restore the health and integrity of the Earth’s ecosystem (Reed, Deakin, & Sunderland, 2015). Landscape approaches to have their roots in the disciplines of conservation and ecology, and are often applied in terms of island biogeography in connection with biodiversity and systems-thinking. (Reed et al., 2015). They consist of viewing the landscape as a continuum of ecosystem functions, and can influence the health of a vineyard (for example, when the landscape is made up of a larger proportion of riparian habitat, vineyards are less prone to Pierce’s disease), considering that carbon sequestration is ten times greater in patches of natural vegetation than in vineyards that are managed (Viers et al., 2013).

# Appendix 2

## Questions for Winegrower Interviews (conducted in French)

1. Do you have any questions about this research project or about the interview?
2. Could you please read and sign and return to me the consent form (that I emailed you prior to the interview)?
3. Are you happy for this interview to be recorded?
4. What is your role and function?
5. How do you identify yourself?
    - ○ Woman
    - ○ Man
    - ○ Other: _______________
6. Who is the owner of the vineyard?
7. What is the size (in hectares) of the vineyard?
8. Is your vineyard certified organic, biodynamic, natural or other?
9. What are the main soil threats to the vineyard?
10. Now I am going to ask you a few questions about soil regeneration management methods in viticulture. Which of the following soil regeneration management methods do you already practice in your vineyard?
    - ○ Interrow cover crop/plant diversity (non-legume)
    - ○ Interrow cover crop (legume)
    - ○ No-till

- Animal integration (sheep, chickens, other)
- Agroforestry
- Non-chemical fertilization
- Non-chemical pest control
- Low traffic (no or reduced tractor or other machinery passage in the vineyard)
- Re-designing vineyard systems at the landscape level

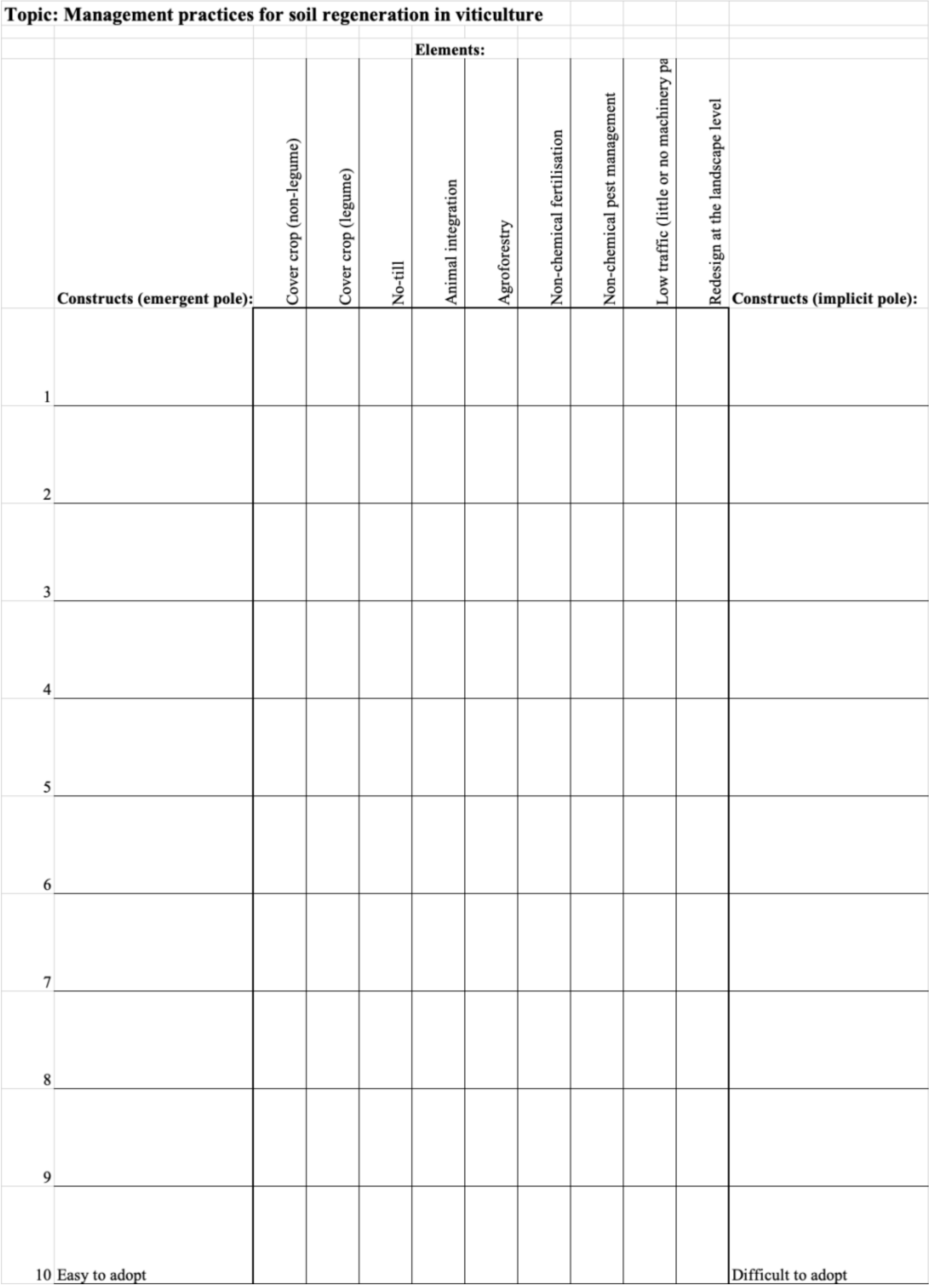
11. Now we are going to play a little game to better understand what enables or hinders you in adopting each of these practices (this will last about 30 minutes). What helps or hinders you in adopting these practices? Let's look at the practices in groups of three. Of these three, which two are the same in some way, and different from the third (in terms of what has helped or hindered you / would help or hinder you in their adoption)? What would be the opposite of that?
    - Construct 1: e.g. My other winemaker friends are doing it - My other winemaker friends are not doing it
    - Great, now I would like you to rate each practice on a scale of one to five, with 'one' being closest to "My other winemaker friends are doing it" and '5' being closest to "My other winemaker friends are not doing it".
    - Construct 2:…
    - (rate)
    - Construct 3:…
    - (rate)
    - Construct 10: (given) Overall, easy to adopt - Overall, difficult to adopt

12. Is there anything else you would like to tell me? What haven’t I asked you that you would like to raise?
13. Can you recommend another winegrower that I should interview?
14. Are you happy to be contacted for follow-up questions or to clarify anything? (if so, what is the best way to reach you?)

THANK YOU

# Appendix 3

## Repertory Grid Used in Interviews (administered in French)



**Topic: Management practices for soil regeneration in viticulture**

**Elements:**

| | **Constructs (emergent pole):** | Cover crop (non-legume) | Cover crop (legume) | No-till | Animal integration | Agroforestry | Non-chemical fertilisation | Non-chemical pest management | Low traffic (little or no machinery pa | Redesign at the landscape level | **Constructs (implicit pole):** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | |
| 2 | | | | | | | | | | | |
| 3 | | | | | | | | | | | |
| 4 | | | | | | | | | | | |
| 5 | | | | | | | | | | | |
| 6 | | | | | | | | | | | |
| 7 | | | | | | | | | | | |
| 8 | | | | | | | | | | | |
| 9 | | | | | | | | | | | |
| 10 | Easy to adopt | | | | | | | | | | Difficult to adopt |

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# Ancillary Appendix 1

## List of References for C Sequestration Comparisons

Table 15. Soil C sequestration figures found by study, practice, and land use.

| Obs. | Practice | t C ha/yr | Author | DOI or link | Land use |
|---|---|---|---|---|---|
| 1 | Agroforestry | 0.74 | Eagle et al. (2011) | https://lter.kbs.msu.edu/docs/robertson/eagle+et+al.+2011+nicholas+inst.pdf | Multi |
| 2 | Agroforestry | 0.62 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |
| 3 | Agroforestry | 1.07 | Perez-Piqueres (2020) | https://doi.org/10.1016/B978-0-12-818732-6.00006-X | Viti/Orch |
| 4 | Agroforestry | -8.65 | Carlisle (1997) | https://doi.org/ 10.1.1.502.1222 | Viti/Orch |
| 5 | Agroforestry | 0.43 | Poulton (1996) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 6 | Agroforestry | 0.56 | Jenkinson (1990) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 7 | Agroforestry | 0.17 | Oelbermann (2006) | https://doi.org/ 10.1007/s10457-005-5963-7 | Vegetable |
| 8 | Agroforestry | 0.22 | Oelbermann (2006) | https://doi.org/ 10.1007/s10457-005-5963-7 | Arable |
| 9 | Agroforestry | 1.79 | Oelbermann (2006) | https://doi.org/ 10.1007/s10457-005-5963-7 | Arable |
| 10 | Agroforestry | 2.34 | Oelbermann (2006) | https://doi.org/ 10.1007/s10457-005-5963-7 | Vegetable |
| 11 | Agroforestry | 0.00 | Peichl (2006) | https://doi.org/10.1007/s10457-005-0361-8 | Vegetable |
| 12 | Agroforestry | 1.04 | Peichl (2006) | https://doi.org/10.1007/s10457-005-0361-8 | Arable |
| 13 | Agroforestry | 4.16 | Beer (1990) | https://doi.org/10.1007/BF00137286 | Arable |
| 14 | Agroforestry | 1.55 | Beer (1990) | https://doi.org/10.1007/BF00137286 | Viti/Orch |
| 15 | Agroforestry | -0.39 | Isaac (2005) | https://doi.org/10.1007/s10457-004-4187-6 | Viti/Orch |
| 16 | Agroforestry | 0.06 | Isaac (2005) | https://doi.org/10.1007/s10457-004-4187-6 | Viti/Orch |
| 17 | Agroforestry | 1.45 | Lal (1999) | https://doi.org/10.1016/j.geoderma.2004.01.021 | Multi |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 18 | Agroforestry | 2.54 | Rocha et al. (2017) | https://www.researchgate.net/publication/318563514 | Multi |
| 19 | Agroforestry | 1.04 | Williams et al. (2011) | https://doi.org/10.1186/1750-0680-6-11 | Viti/Orch |
| 20 | Cover crop (non-legume) | 0.38 | Lei (2017) | ProQuest dissertation number 1993488812 | Arable |
| 21 | Cover crop (non-legume) | 0.17 | Lei (2017) | ProQuest dissertation number 1993488812 | Arable |
| 22 | Cover crop (non-legume) | 0.47 | Lei (2017) | ProQuest dissertation number 1993488812 | Arable |
| 23 | Cover crop (non-legume) | 1.06 | Lei (2017) | ProQuest dissertation number 1993488812 | Arable |
| 24 | Cover crop (non-legume) | 0.23 | Eagle et al. (2011) | https://lter.kbs.msu.edu/docs/robertson/eagle+et+al.+2011+nicholas+inst.pdf | Multi |
| 25 | Cover crop (non-legume) | 1.45 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |
| 26 | Cover crop (non-legume) | 1.92 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |
| 27 | Cover crop (non-legume) | 0.33 | Bolinder et al. (2020) | https://doi.org/ 10.1007/s11027-020-09916-3 | Multi |
| 28 | Cover crop (non-legume) | 2.04 | Marques (2020) | https://doi.org/10.1177/1178622120948069 | Viti/Orch |
| 29 | Cover crop (non-legume) | 0.55 | Tezza (2019) | https://doi.org/10.1016/j.agee.2018.11.002 | Viti/Orch |
| 30 | Cover crop (non-legume) | 2.60 | Gattullo (2020) | https://doi.org/10.3390/agronomy10091334 | Viti/Orch |
| 31 | Cover crop (non-legume) | 0.47 | Peregrina et al.. (2014) | http://dx.doi.org/10.5424/sjar/2014124-5818 | Viti/Orch |
| 32 | Cover crop (non-legume) | 0.25 | Franzluebbers (2005) | https://doi.org/10.1016/j.still.2005.02.012 | Multi |
| 33 | Cover crop (non-legume) | 1.68 | Gu et al. (2016) | https://doi.org/10.1371/journal.pone.0168384 | Viti/Orch |

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|---|---|---|---|---|---|
| 34 | Cover crop (non-legume) | 0.60 | Hutchinson (2007) | https://doi.org/10.1016/j.agrformet.2006.03.030 | Multi |
| 35 | Cover crop (non-legume) | 0.32 | Poeplau & Don (2015) | https://doi.org/10.4141/S03-009 | Multi |
| 36 | Cover crop (non-legume) | 0.32 | Poeplau (2015) | https://doi.org/10.1016/j.agee.2014.10.024 | Multi |
| 37 | Cover crop (non-legume) | 0.40 | Blanco-Canqui (2013) | https://doi.org/10.1016/j.geodrs.2015.01.004 | Multi |
| 38 | Cover crop (non-legume) | 0.28 | Aigulera (2013) | https://doi.org/ 10.1007/s12155-012-9221-3 | Multi |
| 39 | Cover crop (non-legume) | 0.47 | Watson et al. (2000) | https://doi.org/ 10.1046/j.1365-2486.2000.00340.x | Multi |
| 40 | Cover crop (non-legume) | 0.49 | Arrouays et al. (2002) | https://www.researchgate.net/publication/318563514 | Viti/Orch |
| 41 | Cover crop (legume) | 0.66 | Eagle et al. (2011) | https://lter.kbs.msu.edu/docs/robertson/eagle+et+al.+2011+nicholas+inst.pdf | Multi |
| 42 | Cover crop (legume) | 0.30 | Novara (2020) | https://doi.org/10.3390/su12083256 | Viti/Orch |
| 43 | Cover crop (legume) | 1.19 | Peregrina et al. (2014) | http://dx.doi.org/10.5424/sjar/2014124-5818 | Viti/Orch |
| 44 | Cover crop (legume) | 0.07 | Pikula and Rutkowska (2014) | https://doi.org/10.17221/436/2014-PSE | Multi |
| 45 | Cover crop (legume) | 0.51 | West & Post (2002) | https://doi.org/10.1111/j.1475-2743.2005.tb00105.x | Multi |
| 46 | Animal integration | 1.26 | Maillard & Angers (2014) | https://corpus.ulaval.ca/jspui/bitstream/20.500.11794/25374/1/31138.pdf | Multi |
| 47 | Animal integration | 0.60 | Eagle et al. (2011) | https://lter.kbs.msu.edu/docs/robertson/eagle+et+al.+2011+nicholas+inst.pdf | Multi |
| 48 | Animal integration | 0.38 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |

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|---|---|---|---|---|---|
| 49 | Animal integration | 1.47 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.021 | Arable |
| 50 | Animal integration | 0.00 | Francaviglia (2017) | https://doi.org/10.1016/j.scitotenv.2017.05.021 | Viti/Orch |
| 51 | Animal integration | 4.93 | Xue (2020) | https://doi.org/10.1016/j.foreco.2019.117805 | Viti/Orch |
| 52 | Animal integration | 0.76 | Whalen et al. (2008) | https://doi.org/10.4141/CJSS07077 | Arable |
| 53 | Animal integration | 0.28 | Smith (1997) | https://doi.org/10.1007/s10457-004-4187-6 | Viti/Orch |
| 54 | Animal integration | 0.26 | Korschens (2013) | https://doi.org/10.1046/j.1365-2486.1997.00055 | Multi |
| 55 | Animal integration | 0.31 | Maillard (2014) | https://www.soilcare-project.eu/en/downloads/soilcare-reports-and-deliverables/98-report-07-a-review-of-sics-wenr-oene-oenema-full-report-full/file#page=129 | Multi |
| 56 | Animal integration | 3.00 | Teague et al. (2011) | https://doi.org/10.1016/j.scitotenv.2017.11.240 | Viti/Orch |
| 57 | Animal integration | 0.35 | Follett (2001) | https://doi.org/10.2136/sssaj2005.0241 | Multi |
| 58 | Non-chemical fertilizer | 1.10 | Noirot-Cosson (2016) | https://hal.inrae.fr/tel-02797912/document | Multi |
| 59 | Non-chemical fertilizer | 0.65 | Giusani (2013) | https://air.unimi.it/retrieve/handle/2434/233255/303381/phd_unimi_R09036.pdf | Multi |
| 60 | Non-chemical fertilizer | 0.38 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.022 | Arable |
| 61 | Non-chemical fertilizer | 0.69 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.023 | Arable |
| 62 | Non-chemical fertilizer | 0.21 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.024 | Arable |

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|---|---|---|---|---|---|
| 63 | Non-chemical fertilizer | 0.05 | Bais-Moleman et al. (2019) | https://doi.org/10.1016/j.geoderma.2018.11.042 | Arable |
| 64 | Non-chemical fertilizer | 0.12 | Bolinder et al. (2020) | https://doi.org/ 10.1007/s11027-020-09916-3 | Multi |
| 65 | Non-chemical fertilizer | 3.67 | Long et al. (2015) | https://doi.org/10.1016/S2095-3119(14)60796-6 | Arable |
| 66 | Non-chemical fertilizer | 0.52 | Scott et al. (2010) | http://www.grazingbestprac.com.au/research/pastures%20and%20fire/stubble-retention.pdf | Arable |
| 67 | Non-chemical fertilizer | 0.27 | Chiriaco (2019) | https://doi.org/10.1016/j.jclepro.2019.03.192 | Viti/Orch |
| 68 | Non-chemical fertilizer | 0.32 | Chiriaco (2019) | https://doi.org/10.1016/j.jclepro.2019.03.193 | Viti/Orch |
| 69 | Non-chemical fertilizer | 0.16 | Chiriaco (2019) | https://doi.org/10.1016/j.jclepro.2019.03.194 | Viti/Orch |
| 70 | Non-chemical fertilizer | 0.40 | Chiriaco (2019) | https://doi.org/10.1016/j.jclepro.2019.03.195 | Viti/Orch |
| 71 | Non-chemical fertilizer | 0.26 | Fentabil (2016) | https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0228793 | Viti/Orch |
| 72 | Non-chemical fertilizer | 0.05 | Fentabil (2016) | https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0228793 | Viti/Orch |
| 73 | Non-chemical fertilizer | 2.50 | Moffat (2017) | http://scholar.sun.ac.za/handle/10019.1/102977 | Viti/Orch |
| 74 | Non-chemical fertilizer | 0.09 | Francaviglia (2019) | https://doi.org/10.1007/s11027-018-9832-x | Multi |
| 75 | Non-chemical fertilizer | 0.18 | Frankinet et al. (1993) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 76 | Non-chemical fertilizer | 0.50 | Houot et al. (1989) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 77 | Non-chemical fertilizer | 0.45 | Kick & Poletschny (1980) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |

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|---|---|---|---|---|---|
| 78 | Non-chemical fertilizer | 1.04 | M.J. Glendining | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 79 | Non-chemical fertilizer | 1.90 | Thomsen (1993) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 80 | Non-chemical fertilizer | 0.08 | Powlson et al. (1987) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 81 | Non-chemical fertilizer | 0.14 | Powlson et al. (1987) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 82 | Non-chemical fertilizer | 0.67 | Persson & Mattsson (1988) | https://doi.org/ 10.1046/j.1365-2486.1997.00055.x | Arable |
| 83 | Non-chemical fertilizer | 1.00 | Petersen et al. (2013) | http://dx.doi.org/10.1016/j.jclepro.2013.03.007 | Arable |
| 84 | Non-chemical fertilizer | 0.26 | Morlat and Chaussod (2008) | https://www.ajevonline.org/content/59/4/353 | Viti/Orch |
| 85 | Non-chemical fertilizer | 0.58 | Smith (1997) | https://www.soilcare-project.eu/en/downloads/soilcare-reports-and-deliverables/98-report-07-a-review-of-sics-wenr-oene-oenema-full-report-full/file#page=129 | Multi |
| 86 | Non-chemical fertilizer | 0.05 | Liu (2015) | https://doi.org/ 10.1007/s11027-014-9564-5 | Multi |
| 87 | Non-chemical fertilizer | 0.20 | Wang (2015) | https://doi.org/ 10.1007/s10705-015-9710-9 | Multi |
| 88 | Non-chemical fertilizer | 0.12 | VandenBygaart et al. (2003) | https://doi.org/10.4141/S03-009 | Multi |
| 89 | Non-chemical fertilizer | 1.74 | Roldan et al. (2003) | https://doi.org/10.1016/S0167-1987(03)00051-5 | Vegetable |
| 90 | Non-chemical fertilizer | 0.31 | Alvear et al. (2005) | https://doi.org/10.1016/j.still.2004.06.002 | Vegetable |
| 91 | Non-chemical fertilizer | 0.35 | Metay et al. (2007) | https://doi.org/10.1016/j.still.2006.07.009 | Multi |

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|---|---|---|---|---|---|
| 92 | Non-chemical fertilizer | 0.77 | Andrews et al. 2002 | https://doi.org/10.1073/pnas.1209429110 | Multi |
| 93 | Non-chemical fertilizer | 2.01 | Armstrong et al. 2000_arable | https://doi.org/10.1073/pnas.1209429111 | Vegetable |
| 94 | Non-chemical fertilizer | 2.89 | Armstrong et al. 2000_horticulture | https://doi.org/10.1073/pnas.1209429112 | Arable |
| 95 | Non-chemical fertilizer | -1.14 | Armstrong et al. 2000_pasture | https://doi.org/10.1073/pnas.1209429113 | Vegetable |
| 96 | Non-chemical fertilizer | 4.07 | Benitez et al. 2006-Cordoba_1 | https://doi.org/10.1073/pnas.1209429114 | Grassland |
| 97 | Non-chemical fertilizer | 0.87 | Benitez et al. 2006-Cordoba_2 | https://doi.org/10.1073/pnas.1209429115 | Viti/Orch |
| 98 | Non-chemical fertilizer | 1.69 | Benitez et al. 2006-Cordoba_3 | https://doi.org/10.1073/pnas.1209429116 | Viti/Orch |
| 99 | Non-chemical fertilizer | -1.52 | Benitez et al. 2006-Cordoba_4 | https://doi.org/10.1073/pnas.1209429117 | Viti/Orch |
| 100 | Non-chemical fertilizer | 2.05 | Benitez et al. 2006-Granada_1 | https://doi.org/10.1073/pnas.1209429118 | Viti/Orch |
| 101 | Non-chemical fertilizer | 1.95 | Benitez et al. 2006-Granada_2 | https://doi.org/10.1073/pnas.1209429119 | Viti/Orch |
| 102 | Non-chemical fertilizer | -2.69 | Benitez et al. 2006-Granada_3 | https://doi.org/10.1073/pnas.1209429120 | Viti/Orch |
| 103 | Non-chemical fertilizer | -2.59 | Benitez et al. 2006-Granada_4 | https://doi.org/10.1073/pnas.1209429121 | Viti/Orch |
| 104 | Non-chemical fertilizer | -0.49 | Benitez et al. 2006-Granada_5 | https://doi.org/10.1073/pnas.1209429122 | Viti/Orch |
| 105 | Non-chemical fertilizer | -0.59 | Benitez et al. 2006-Granada_6 | https://doi.org/10.1073/pnas.1209429123 | Viti/Orch |
| 106 | Non-chemical fertilizer | 1.06 | Blaise, 2006 | https://doi.org/10.1073/pnas.1209429124 | Viti/Orch |

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|---|---|---|---|---|---|
| 107 | Non-chemical fertilizer | 0.66 | Blakemore 2000_Haughley 1 | https://doi.org/10.1073/pnas.1209429125 | Arable |
| 108 | Non-chemical fertilizer | 1.15 | Blakemore 2000_Haughley 2 | https://doi.org/10.1073/pnas.1209429126 | Arable |
| 109 | Non-chemical fertilizer | 0.07 | Campos-Herrera et al. 2010_apple orchard | https://doi.org/10.1073/pnas.1209429127 | Arable |
| 110 | Non-chemical fertilizer | 0.20 | Campos-Herrera et al. 2010_cropland | https://doi.org/10.1073/pnas.1209429128 | Viti/Orch |
| 111 | Non-chemical fertilizer | 1.40 | Campos-Herrera et al. 2010_vineyard | https://doi.org/10.1073/pnas.1209429129 | Arable |
| 112 | Non-chemical fertilizer | 0.90 | Canali et al. 2009 | https://doi.org/10.1073/pnas.1209429130 | Viti/Orch |
| 113 | Non-chemical fertilizer | 0.94 | Capriel 1991_ Farm Pair 1 | https://doi.org/10.1073/pnas.1209429131 | Viti/Orch |
| 114 | Non-chemical fertilizer | -0.07 | Capriel 1991_Farm Pair 2 | https://doi.org/10.1073/pnas.1209429132 | Arable |
| 115 | Non-chemical fertilizer | 0.91 | Capriel 1991_Farm Pair 3 | https://doi.org/10.1073/pnas.1209429133 | Arable |
| 116 | Non-chemical fertilizer | 0.99 | Capriel 1991_Farm Pair 4 | https://doi.org/10.1073/pnas.1209429134 | Arable |
| 117 | Non-chemical fertilizer | 1.18 | Capriel 1991_Farm Pair 5 | https://doi.org/10.1073/pnas.1209429135 | Arable |
| 118 | Non-chemical fertilizer | 0.58 | Chirinda et al. 2010_Flakkeberg 1 | https://doi.org/10.1073/pnas.1209429136 | Arable |
| 119 | Non-chemical fertilizer | 0.48 | Chirinda et al. 2010_Flakkeberg 2 | https://doi.org/10.1073/pnas.1209429137 | Arable |
| 120 | Non-chemical fertilizer | 0.71 | Chirinda et al. 2010_Flakkeberg 3 | https://doi.org/10.1073/pnas.1209429138 | Arable |
| 121 | Non-chemical fertilizer | 1.49 | Chirinda et al. 2010_Foulum 1 | https://doi.org/10.1073/pnas.1209429139 | Arable |

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|---|---|---|---|---|---|
| 122 | Non-chemical fertilizer | 0.39 | Chirinda et al. 2010_Foulum 2 | https://doi.org/10.1073/pnas.1209429140 | Arable |
| 123 | Non-chemical fertilizer | 1.46 | Chirinda et al. 2010_Foulum 3 | https://doi.org/10.1073/pnas.1209429141 | Arable |
| 124 | Non-chemical fertilizer | 0.25 | Ciavatta et al. 2008_subsoil | https://doi.org/10.1073/pnas.1209429142 | Arable |
| 125 | Non-chemical fertilizer | 0.63 | Ciavatta et al. 2008_topsoil | https://doi.org/10.1073/pnas.1209429143 | Viti/Orch |
| 126 | Non-chemical fertilizer | 0.23 | Clark et al. 1998_SAFS 1 | https://doi.org/10.1073/pnas.1209429144 | Viti/Orch |
| 127 | Non-chemical fertilizer | 0.38 | Clark et al. 1998_SAFS 2 | https://doi.org/10.1073/pnas.1209429145 | Arable |
| 128 | Non-chemical fertilizer | 0.53 | Clark et al. 1998_SAFS 3 | https://doi.org/10.1073/pnas.1209429146 | Arable |
| 129 | Non-chemical fertilizer | 0.65 | Delate and Cambardella 2004_1 | https://doi.org/10.1073/pnas.1209429147 | Arable |
| 130 | Non-chemical fertilizer | 0.55 | Delate and Cambardella 2004_2 | https://doi.org/10.1073/pnas.1209429148 | Arable |
| 131 | Non-chemical fertilizer | 0.37 | Delate and Cambardella 2004_3 | https://doi.org/10.1073/pnas.1209429149 | Arable |
| 132 | Non-chemical fertilizer | -0.35 | Deria et al. 2003_site 1 | https://doi.org/10.1073/pnas.1209429150 | Arable |
| 133 | Non-chemical fertilizer | -0.10 | Deria et al. 2003_site 2 | https://doi.org/10.1073/pnas.1209429151 | Arable |
| 134 | Non-chemical fertilizer | 0.05 | Deria et al. 2003_site 3 | https://doi.org/10.1073/pnas.1209429152 | Arable |
| 135 | Non-chemical fertilizer | -0.33 | Deria et al. 2003_site 4 | https://doi.org/10.1073/pnas.1209429153 | Arable |
| 136 | Non-chemical fertilizer | 0.40 | Deria et al. 2003_site 5 | https://doi.org/10.1073/pnas.1209429154 | Arable |

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|---|---|---|---|---|---|
| 137 | Non-chemical fertilizer | 0.20 | Deria et al. 2003_site 6 | https://doi.org/10.1073/pnas.1209429155 | Arable |
| 138 | Non-chemical fertilizer | -0.05 | Deria et al. 2003_site 7 | https://doi.org/10.1073/pnas.1209429156 | Arable |
| 139 | Non-chemical fertilizer | 0.07 | Derrick & Dumaresq 1999 | https://doi.org/10.1073/pnas.1209429157 | Arable |
| 140 | Non-chemical fertilizer | 0.55 | Diez et al. 1991 | https://doi.org/10.1073/pnas.1209429158 | Arable |
| 141 | Non-chemical fertilizer | 0.00 | Dilly et al., 2001, Scheyern single croplands I | https://doi.org/10.1073/pnas.1209429159 | Arable |
| 142 | Non-chemical fertilizer | 0.00 | Dilly et al., 2001, Scheyern single grasslands | https://doi.org/10.1073/pnas.1209429160 | Arable |
| 143 | Non-chemical fertilizer | -0.16 | Droogers & Bouma 1996_arable subsoil | https://doi.org/10.1073/pnas.1209429161 | Grassland |
| 144 | Non-chemical fertilizer | 0.11 | Droogers & Bouma 1996_arable topsoil | https://doi.org/10.1073/pnas.1209429162 | Arable |
| 145 | Non-chemical fertilizer | 0.08 | Droogers & Bouma 1996_grass subsoil | https://doi.org/10.1073/pnas.1209429163 | Arable |
| 146 | Non-chemical fertilizer | 0.67 | Droogers & Bouma 1996_grass topsoil | https://doi.org/10.1073/pnas.1209429164 | Grassland |
| 147 | Non-chemical fertilizer | -1.13 | Efthimiadou et al. 2010_1 | https://doi.org/10.1073/pnas.1209429165 | Grassland |
| 148 | Non-chemical fertilizer | -1.11 | Efthimiadou et al. 2010_2 | https://doi.org/10.1073/pnas.1209429166 | Arable |
| 149 | Non-chemical fertilizer | 1.21 | Eltun et al. 2002_arable 1 | https://doi.org/10.1073/pnas.1209429167 | Arable |
| 150 | Non-chemical fertilizer | -1.26 | Eltun et al. 2002_arable 2 | https://doi.org/10.1073/pnas.1209429168 | Arable |
| 151 | Non-chemical fertilizer | -3.38 | Eltun et al. 2002_forage 1 | https://doi.org/10.1073/pnas.1209429169 | Arable |

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| 152 | Non-chemical fertilizer | -3.81 | Eltun et al. 2002_forage 2 | https://doi.org/10.1073/pnas.1209429170 | Arable |
| 153 | Non-chemical fertilizer | 0.06 | Eyhorn et al. 2007 | https://doi.org/10.1073/pnas.1209429171 | Arable |
| 154 | Non-chemical fertilizer | 1.66 | Fraser et al. 1988_pair1_total | https://doi.org/10.1073/pnas.1209429172 | Arable |
| 155 | Non-chemical fertilizer | 1.53 | Fraser et al. 1988_pair2_total | https://doi.org/10.1073/pnas.1209429173 | Arable |
| 156 | Non-chemical fertilizer | 1.86 | Fraser et al. 1988_pair3_total | https://doi.org/10.1073/pnas.1209429174 | Arable |
| 157 | Non-chemical fertilizer | 0.55 | Friedel et al. 2000 | https://doi.org/10.1073/pnas.1209429175 | Arable |
| 158 | Non-chemical fertilizer | 3.28 | Garcia-Ruizet al. 2009_PG site | https://doi.org/10.1073/pnas.1209429176 | Viti/Orch |
| 159 | Non-chemical fertilizer | 1.96 | Garcia-Ruizet al. 2009_PS site | https://doi.org/10.1073/pnas.1209429177 | Viti/Orch |
| 160 | Non-chemical fertilizer | 1.98 | Garcia-Ruizet al. 2009_PT site | https://doi.org/10.1073/pnas.1209429178 | Viti/Orch |
| 161 | Non-chemical fertilizer | 0.99 | Gardner & Glancy, 1996_ND Central-1 | https://doi.org/10.1073/pnas.1209429179 | Arable |
| 162 | Non-chemical fertilizer | -0.92 | Gardner & Glancy, 1996_ND Central-2 | https://doi.org/10.1073/pnas.1209429180 | Arable |
| 163 | Non-chemical fertilizer | 1.40 | Gardner & Glancy, 1996_ND East-1 | https://doi.org/10.1073/pnas.1209429181 | Arable |
| 164 | Non-chemical fertilizer | -1.15 | Gardner & Glancy, 1996_ND East-2 | https://doi.org/10.1073/pnas.1209429182 | Arable |
| 165 | Non-chemical fertilizer | -0.24 | Gardner & Glancy, 1996_ND West-1 | https://doi.org/10.1073/pnas.1209429183 | Arable |
| 166 | Non-chemical fertilizer | -0.62 | Gardner & Glancy, 1996_ND West-2 | https://doi.org/10.1073/pnas.1209429184 | Arable |

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| 167 | Non-chemical fertilizer | 4.31 | Ge et al., 2011 | https://doi.org/10.1073/pnas.1209429185 | Arable |
| 168 | Non-chemical fertilizer | 1.14 | Gehrhardt, 1997 | https://doi.org/10.1073/pnas.1209429186 | Vegetable |
| 169 | Non-chemical fertilizer | 1.30 | Glover et al. 2000_orchard 1 | https://doi.org/10.1073/pnas.1209429187 | Arable |
| 170 | Non-chemical fertilizer | 0.47 | Glover et al. 2000_orchard 2 | https://doi.org/10.1073/pnas.1209429188 | Viti/Orch |
| 171 | Non-chemical fertilizer | 0.66 | Gosling & Shepherd 2005_pair 1 | https://doi.org/10.1073/pnas.1209429189 | Viti/Orch |
| 172 | Non-chemical fertilizer | 0.22 | Gosling & Shepherd 2005_pair 2 | https://doi.org/10.1073/pnas.1209429190 | Arable |
| 173 | Non-chemical fertilizer | 0.13 | Grandy & Robertson 2007_pair 1 | https://doi.org/10.1073/pnas.1209429191 | Arable |
| 174 | Non-chemical fertilizer | 0.02 | Grandy & Robertson 2007_pair 2 | https://doi.org/10.1073/pnas.1209429192 | Arable |
| 175 | Non-chemical fertilizer | -0.10 | Grandy & Robertson 2007_pair 3 | https://doi.org/10.1073/pnas.1209429193 | Arable |
| 176 | Non-chemical fertilizer | -0.11 | Granstedt et al. 2008_subsoil | https://doi.org/10.1073/pnas.1209429194 | Arable |
| 177 | Non-chemical fertilizer | 0.11 | Granstedt et al. 2008_topsoil | https://doi.org/10.1073/pnas.1209429195 | Arable |
| 178 | Non-chemical fertilizer | 0.35 | Haggar et al. 2011_Costa Rica, CE | https://doi.org/10.1073/pnas.1209429196 | Arable |
| 179 | Non-chemical fertilizer | 0.49 | Haggar et al. 2011_Costa Rica, CEEP | https://doi.org/10.1073/pnas.1209429197 | Viti/Orch |
| 180 | Non-chemical fertilizer | 0.94 | Haggar et al. 2011_Costa Rica, CETA | https://doi.org/10.1073/pnas.1209429198 | Viti/Orch |
| 181 | Non-chemical fertilizer | 1.05 | Haggar et al. 2011_Costa Rica, EP | https://doi.org/10.1073/pnas.1209429199 | Viti/Orch |

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| 182 | Non-chemical fertilizer | 0.45 | Haggar et al. 2011_Costa Rica, EPTA | https://doi.org/10.1073/pnas.1209429200 | Viti/Orch |
| 183 | Non-chemical fertilizer | 0.29 | Haggar et al. 2011_Costa Rica, TA | https://doi.org/10.1073/pnas.1209429201 | Viti/Orch |
| 184 | Non-chemical fertilizer | -0.51 | Haggar et al. 2011_Nicaragua ILSG | https://doi.org/10.1073/pnas.1209429202 | Viti/Orch |
| 185 | Non-chemical fertilizer | 1.07 | Haggar et al. 2011_Nicaragua ILSS | https://doi.org/10.1073/pnas.1209429203 | Viti/Orch |
| 186 | Non-chemical fertilizer | -1.38 | Haggar et al. 2011_Nicaragua SGTR | https://doi.org/10.1073/pnas.1209429204 | Viti/Orch |
| 187 | Non-chemical fertilizer | 0.12 | Heitkamp et al. 2009_high fert. | https://doi.org/10.1073/pnas.1209429205 | Viti/Orch |
| 188 | Non-chemical fertilizer | 0.11 | Heitkamp et al. 2009_low fert. | https://doi.org/10.1073/pnas.1209429206 | Arable |
| 189 | Non-chemical fertilizer | 0.16 | Heitkamp et al. 2009_medium fert. | https://doi.org/10.1073/pnas.1209429207 | Arable |
| 190 | Non-chemical fertilizer | 0.95 | Hepperly et al. 2006_pair 1 | https://doi.org/10.1073/pnas.1209429208 | Arable |
| 191 | Non-chemical fertilizer | 0.76 | Hepperly et al. 2006_pair 2 | https://doi.org/10.1073/pnas.1209429209 | Arable |
| 192 | Non-chemical fertilizer | 1.48 | Herencia Galan et al. 2011 | https://doi.org/10.1073/pnas.1209429210 | Arable |
| 193 | Non-chemical fertilizer | 0.07 | Kahle et al. 2005 | https://doi.org/10.1073/pnas.1209429211 | Vegetable |
| 194 | Non-chemical fertilizer | 0.39 | Kirchmann et al. 2007 | https://doi.org/10.1073/pnas.1209429212 | Arable |
| 195 | Non-chemical fertilizer | 0.41 | Kong et al. 2005_pair 3 | https://doi.org/10.1073/pnas.1209429213 | Arable |
| 196 | Non-chemical fertilizer | 0.46 | Kong et al. 2005_pair 1 | https://doi.org/10.1073/pnas.1209429214 | Arable |

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| 197 | Non-chemical fertilizer | 0.47 | Kong et al. 2005_pair 2 | https://doi.org/10.1073/pnas.1209429215 | Arable |
| 198 | Non-chemical fertilizer | 0.57 | Kramer et al. 2006_orchard 1 | https://doi.org/10.1073/pnas.1209429216 | Arable |
| 199 | Non-chemical fertilizer | 0.15 | Kramer et al. 2006_orchard 2 | https://doi.org/10.1073/pnas.1209429217 | Viti/Orch |
| 200 | Non-chemical fertilizer | 0.11 | Leifeld et al. 2009_DOK 1 | https://doi.org/10.1073/pnas.1209429218 | Viti/Orch |
| 201 | Non-chemical fertilizer | 0.03 | Leifeld et al. 2009_DOK 2 | https://doi.org/10.1073/pnas.1209429219 | Arable |
| 202 | Non-chemical fertilizer | 0.03 | Leifeld et al. 2009_DOK 3 | https://doi.org/10.1073/pnas.1209429220 | Arable |
| 203 | Non-chemical fertilizer | -0.05 | Leifeld et al. 2009_DOK 4 | https://doi.org/10.1073/pnas.1209429221 | Arable |
| 204 | Non-chemical fertilizer | 0.07 | Leite et al. 2010_total horizon_pair 1 | https://doi.org/10.1073/pnas.1209429222 | Arable |
| 205 | Non-chemical fertilizer | 0.06 | Leite et al. 2010_total horizon_pair 2 | https://doi.org/10.1073/pnas.1209429223 | Vegetable |
| 206 | Non-chemical fertilizer | 1.70 | Liebig & Doran 1999_Deweese | https://doi.org/10.1073/pnas.1209429224 | Vegetable |
| 207 | Non-chemical fertilizer | 0.66 | Liebig & Doran 1999_Giltner | https://doi.org/10.1073/pnas.1209429225 | Arable |
| 208 | Non-chemical fertilizer | 1.59 | Liebig & Doran 1999_Medina | https://doi.org/10.1073/pnas.1209429226 | Arable |
| 209 | Non-chemical fertilizer | 1.02 | Liebig & Doran 1999_Valley | https://doi.org/10.1073/pnas.1209429227 | Arable |
| 210 | Non-chemical fertilizer | 0.61 | Liebig & Doran 1999_Windsor | https://doi.org/10.1073/pnas.1209429228 | Arable |
| 211 | Non-chemical fertilizer | 1.89 | Lytton-Hitchins et al. 1994 | https://doi.org/10.1073/pnas.1209429229 | Arable |

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| 212 | Non-chemical fertilizer | 0.47 | Marinari et al. 2010b_Colle Valle farm scale | https://doi.org/10.1073/pnas.1209429230 | Grassland |
| 213 | Non-chemical fertilizer | 0.48 | Marinari et al. 2010a_Colle Valle plot scale | https://doi.org/10.1073/pnas.1209429231 | Arable |
| 214 | Non-chemical fertilizer | -0.56 | Marinari et al. 2010b_La Selva | https://doi.org/10.1073/pnas.1209429232 | Arable |
| 215 | Non-chemical fertilizer | 0.85 | Mazzoncini et al. 2010 | https://doi.org/10.1073/pnas.1209429233 | Arable |
| 216 | Non-chemical fertilizer | 1.24 | Melero et al. 2007_pair 1 | https://doi.org/10.1073/pnas.1209429234 | Arable |
| 217 | Non-chemical fertilizer | 1.73 | Melero et al. 2007_pair 2 | https://doi.org/10.1073/pnas.1209429235 | Arable |
| 218 | Non-chemical fertilizer | 2.35 | Moeskops et al. 2010_Cisarua1 Pair 1 | https://doi.org/10.1073/pnas.1209429236 | Arable |
| 219 | Non-chemical fertilizer | 2.07 | Moeskops et al. 2010_Cisarua1 Pair 2 | https://doi.org/10.1073/pnas.1209429237 | Vegetable |
| 220 | Non-chemical fertilizer | -0.04 | Moeskops et al. 2010_Cisarua2 Pair 1 | https://doi.org/10.1073/pnas.1209429238 | Vegetable |
| 221 | Non-chemical fertilizer | -0.10 | Moeskops et al. 2010_Cisarua2 Pair 2 | https://doi.org/10.1073/pnas.1209429239 | Vegetable |
| 222 | Non-chemical fertilizer | 5.92 | Moeskops et al. 2010_Ciwidey Pair 1 | https://doi.org/10.1073/pnas.1209429240 | Vegetable |
| 223 | Non-chemical fertilizer | 4.04 | Moeskops et al. 2010_Ciwidey Pair 2 | https://doi.org/10.1073/pnas.1209429241 | Vegetable |
| 224 | Non-chemical fertilizer | 0.12 | Mulla et al. 1992_backslope | https://doi.org/10.1073/pnas.1209429242 | Vegetable |
| 225 | Non-chemical fertilizer | 0.31 | Mulla et al. 1992_footslope | https://doi.org/10.1073/pnas.1209429243 | Arable |

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| 226 | Non-chemical fertilizer | 0.12 | Mulla et al. 1992_topslope | https://doi.org/10.1073/pnas.1209429244 | Arable |
| 227 | Non-chemical fertilizer | 0.17 | Murata & Goh, 1997_arable | https://doi.org/10.1073/pnas.1209429245 | Arable |
| 228 | Non-chemical fertilizer | 0.18 | Murata & Goh, 1997_pasture | https://doi.org/10.1073/pnas.1209429246 | Arable |
| 229 | Non-chemical fertilizer | -1.28 | N. Monokrousos et al. 2006_pair 1 | https://doi.org/10.1073/pnas.1209429247 | Grassland |
| 230 | Non-chemical fertilizer | -0.91 | N. Monokrousos et al. 2006_pair 2 | https://doi.org/10.1073/pnas.1209429248 | Vegetable |
| 231 | Non-chemical fertilizer | -1.82 | N. Monokrousos et al. 2006_pair 3 | https://doi.org/10.1073/pnas.1209429249 | Vegetable |
| 232 | Non-chemical fertilizer | 0.00 | Nguyen et al. 1995_Kowai cropland | https://doi.org/10.1073/pnas.1209429250 | Vegetable |
| 233 | Non-chemical fertilizer | 0.38 | Nguyen et al. 1995_Kowai pasture | https://doi.org/10.1073/pnas.1209429251 | Arable |
| 234 | Non-chemical fertilizer | 0.09 | Nguyen et al. 1995_Templeton cropland | https://doi.org/10.1073/pnas.1209429252 | Grassland |
| 235 | Non-chemical fertilizer | 0.09 | Nguyen et al. 1995_Templeton pasture | https://doi.org/10.1073/pnas.1209429253 | Arable |
| 236 | Non-chemical fertilizer | -0.09 | Nguyen et al. 1995_Temuka cropland | https://doi.org/10.1073/pnas.1209429254 | Grassland |
| 237 | Non-chemical fertilizer | 0.09 | Nguyen et al. 1995_Temuka pasture | https://doi.org/10.1073/pnas.1209429255 | Arable |
| 238 | Non-chemical fertilizer | 0.07 | Oberholzer et al. 2000 | https://doi.org/10.1073/pnas.1209429256 | Grassland |
| 239 | Non-chemical fertilizer | 0.08 | Okur et al. 2009 | https://doi.org/10.1073/pnas.1209429257 | Arable |
| 240 | Non-chemical fertilizer | -0.22 | Pardo et al. 2009_plot 1 | https://doi.org/10.1073/pnas.1209429258 | Viti/Orch |

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| 241 | Non-chemical fertilizer | 1.58 | Pardo et al. 2009_plot 2 | https://doi.org/10.1073/pnas.1209429259 | Arable |
| 242 | Non-chemical fertilizer | 0.66 | Petersen et al. 1997_pair 1 | https://doi.org/10.1073/pnas.1209429260 | Arable |
| 243 | Non-chemical fertilizer | 0.66 | Petersen et al. 1997_pair 2 | https://doi.org/10.1073/pnas.1209429261 | Arable |
| 244 | Non-chemical fertilizer | 0.36 | Petersen et al. 1997_pair 3 | https://doi.org/10.1073/pnas.1209429262 | Arable |
| 245 | Non-chemical fertilizer | 0.08 | Petersen et al. 1997_pair 4 | https://doi.org/10.1073/pnas.1209429263 | Arable |
| 246 | Non-chemical fertilizer | 0.59 | Petersen et al. 1997_pair 5 | https://doi.org/10.1073/pnas.1209429264 | Arable |
| 247 | Non-chemical fertilizer | 0.59 | Petersen et al. 1997_pair 6 | https://doi.org/10.1073/pnas.1209429265 | Arable |
| 248 | Non-chemical fertilizer | 0.29 | Petersen et al. 1997_pair 7 | https://doi.org/10.1073/pnas.1209429266 | Arable |
| 249 | Non-chemical fertilizer | 0.01 | Petersen et al. 1997_pair 8 | https://doi.org/10.1073/pnas.1209429267 | Arable |
| 250 | Non-chemical fertilizer | 0.25 | Phillips, 2007 | https://doi.org/10.1073/pnas.1209429268 | Arable |
| 251 | Non-chemical fertilizer | 0.36 | Probst et al. 2008_P-I-bottom | https://doi.org/10.1073/pnas.1209429269 | Arable |
| 252 | Non-chemical fertilizer | 0.45 | Probst et al. 2008_P-II-bottom | https://doi.org/10.1073/pnas.1209429270 | Viti/Orch |
| 253 | Non-chemical fertilizer | 0.29 | Probst et al. 2008_P-II-top | https://doi.org/10.1073/pnas.1209429271 | Viti/Orch |
| 254 | Non-chemical fertilizer | 0.01 | Probst et al. 2008_P-I-top | https://doi.org/10.1073/pnas.1209429272 | Viti/Orch |
| 255 | Non-chemical fertilizer | -1.60 | Probst et al. 2008_T-I-bottom | https://doi.org/10.1073/pnas.1209429273 | Viti/Orch |

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| 256 | Non-chemical fertilizer | -1.75 | Probst et al. 2008_T-II-bottom | https://doi.org/10.1073/pnas.1209429274 | Viti/Orch |
| 257 | Non-chemical fertilizer | -2.52 | Probst et al. 2008_T-II-top | https://doi.org/10.1073/pnas.1209429275 | Viti/Orch |
| 258 | Non-chemical fertilizer | -1.17 | Probst et al. 2008_T-I-top | https://doi.org/10.1073/pnas.1209429276 | Viti/Orch |
| 259 | Non-chemical fertilizer | 0.11 | Pulleman et al. 2003 | https://doi.org/10.1073/pnas.1209429277 | Viti/Orch |
| 260 | Non-chemical fertilizer | 0.10 | Purin et al. 2006 | https://doi.org/10.1073/pnas.1209429278 | Arable |
| 261 | Non-chemical fertilizer | -0.39 | Qin et al. 2010 | https://doi.org/10.1073/pnas.1209429279 | Viti/Orch |
| 262 | Non-chemical fertilizer | 1.20 | Rasul and Thapa 2004 | https://doi.org/10.1073/pnas.1209429280 | Arable |
| 263 | Non-chemical fertilizer | 1.17 | Reganold et al. 1993_citrus | https://doi.org/10.1073/pnas.1209429281 | Arable |
| 264 | Non-chemical fertilizer | -0.76 | Reganold et al. 1993_dairy_clay loam | https://doi.org/10.1073/pnas.1209429282 | Viti/Orch |
| 265 | Non-chemical fertilizer | 1.05 | Reganold et al. 1993_dairy_sandy loam | https://doi.org/10.1073/pnas.1209429283 | Grassland |
| 266 | Non-chemical fertilizer | -1.43 | Reganold et al. 1993_grain | https://doi.org/10.1073/pnas.1209429284 | Grassland |
| 267 | Non-chemical fertilizer | 1.89 | Reganold et al. 1993_market garden | https://doi.org/10.1073/pnas.1209429285 | Arable |
| 268 | Non-chemical fertilizer | 1.53 | Reganold et al. 1993_pip fruit | https://doi.org/10.1073/pnas.1209429286 | Vegetable |
| 269 | Non-chemical fertilizer | 1.22 | Reganold et al. 1993_sheep | https://doi.org/10.1073/pnas.1209429287 | Viti/Orch |
| 270 | Non-chemical fertilizer | 1.01 | Reganold et al. 2010_subsoil | https://doi.org/10.1073/pnas.1209429288 | Grassland |

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| 271 | Non-chemical fertilizer | 0.35 | Reganold et al. 2010_topsoil | https://doi.org/10.1073/pnas.1209429289 | Vegetable |
| 272 | Non-chemical fertilizer | 0.24 | Romanya and Rovira, 2009_irrigated | https://doi.org/10.1073/pnas.1209429290 | Vegetable |
| 273 | Non-chemical fertilizer | -0.10 | Romanya and Rovira, 2009_rain-fed | https://doi.org/10.1073/pnas.1209429291 | Arable |
| 274 | Non-chemical fertilizer | 0.34 | Rühling et al. 2005, Scheyern all fields | https://doi.org/10.1073/pnas.1209429292 | Arable |
| 275 | Non-chemical fertilizer | -0.11 | Schjønning et al. 2002_group I_pair 1 | https://doi.org/10.1073/pnas.1209429293 | Arable |
| 276 | Non-chemical fertilizer | -0.04 | Schjønning et al. 2002_group I_pair 2 | https://doi.org/10.1073/pnas.1209429294 | Arable |
| 277 | Non-chemical fertilizer | 0.09 | Schjønning et al. 2002_group II | https://doi.org/10.1073/pnas.1209429295 | Arable |
| 278 | Non-chemical fertilizer | 0.32 | Schjønning et al. 2002_group III | https://doi.org/10.1073/pnas.1209429296 | Arable |
| 279 | Non-chemical fertilizer | -0.05 | Sehy, 2004, Scheyern single croplands II | https://doi.org/10.1073/pnas.1209429297 | Arable |
| 280 | Non-chemical fertilizer | 0.94 | Snapp et al. 2010 | https://doi.org/10.1073/pnas.1209429298 | Arable |
| 281 | Non-chemical fertilizer | 0.75 | Teasdale et al. 2007_total horizon_pair 1 | https://doi.org/10.1073/pnas.1209429299 | Arable |
| 282 | Non-chemical fertilizer | 0.51 | Teasdale et al. 2007_total horizon_pair 2 | https://doi.org/10.1073/pnas.1209429300 | Arable |
| 283 | Non-chemical fertilizer | 0.80 | Teasdale et al. 2007_total horizon_pair 3 | https://doi.org/10.1073/pnas.1209429301 | Arable |
| 284 | Non-chemical fertilizer | 0.05 | Van Diepeningen et al. 2006, clay soils | https://doi.org/10.1073/pnas.1209429302 | Arable |
| 285 | Non-chemical fertilizer | 0.60 | Van Diepeningen et al. 2006, sandy soils | https://doi.org/10.1073/pnas.1209429303 | Arable |

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| 286 | Non-chemical fertilizer | -0.30 | Vavoulidou et al. 2009_Arkadia | https://doi.org/10.1073/pnas.1209429304 | Arable |
| 287 | Non-chemical fertilizer | 2.40 | Vavoulidou et al. 2009_Attiki | https://doi.org/10.1073/pnas.1209429305 | Viti/Orch |
| 288 | Non-chemical fertilizer | 0.60 | Vavoulidou et al. 2009_Chania citrus | https://doi.org/10.1073/pnas.1209429306 | Viti/Orch |
| 289 | Non-chemical fertilizer | -3.60 | Vavoulidou et al. 2009_Chania olive | https://doi.org/10.1073/pnas.1209429307 | Viti/Orch |
| 290 | Non-chemical fertilizer | -6.50 | Vavoulidou et al. 2009_Mesinia | https://doi.org/10.1073/pnas.1209429308 | Viti/Orch |
| 291 | Non-chemical fertilizer | 0.14 | Wang et al. 2011_pair 1 | https://doi.org/10.1073/pnas.1209429309 | Viti/Orch |
| 292 | Non-chemical fertilizer | 0.42 | Wang et al. 2011_pair 2 | https://doi.org/10.1073/pnas.1209429310 | Vegetable |
| 293 | Non-chemical fertilizer | 1.00 | Wang et al. 2011_pair 3 | https://doi.org/10.1073/pnas.1209429311 | Vegetable |
| 294 | Non-chemical fertilizer | 1.72 | Wells et al 2000_pair 1 | https://doi.org/10.1073/pnas.1209429312 | Vegetable |
| 295 | Non-chemical fertilizer | 3.28 | Wells et al. 2000_pair 2 | https://doi.org/10.1073/pnas.1209429313 | Vegetable |
| 296 | Non-chemical fertilizer | 2.02 | Wells et al. 2000_pair 3 | https://doi.org/10.1073/pnas.1209429314 | Vegetable |
| 297 | Non-chemical fertilizer | -1.00 | Wells et al. 2000_pair 4 | https://doi.org/10.1073/pnas.1209429315 | Vegetable |
| 298 | Non-chemical fertilizer | 0.00 | Welsh et al. 2009_forage-grain | https://doi.org/10.1073/pnas.1209429316 | Vegetable |
| 299 | Non-chemical fertilizer | -0.33 | Welsh et al. 2009_grain only | https://doi.org/10.1073/pnas.1209429317 | Arable |
| 300 | Non-chemical fertilizer | 0.00 | Welsh et al. 2009_forage-grain compost | https://doi.org/10.1073/pnas.1209429318 | Arable |

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| 301 | Non-chemical pest mgmt | 0.54 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |
| 302 | Non-chemical pest mgmt | 0.60 | Petersen et al. (2013) | http://dx.doi.org/10.1016/j.jclepro.2013.03.007 | Arable |
| 303 | Non-chemical pest mgmt | 1.86 | Salomé et al. (2016) | https://doi.org/10.1016/j.ecolind.2015.09.047 | Viti/Orch |
| 304 | Non-chemical pest mgmt | 1.15 | Perie and Munson (2000) | https://doi.org/10.1016/S0167-1987(02)00021-1 | Arable |
| 305 | Non-chemical pest mgmt | 1.25 | Marriott & Wander (2006) | https://doi.org/10.2136/sssaj2005.0241 | Grassland |
| 306 | No-tillage | 0.29 | Eagle et al. (2011) | https://lter.kbs.msu.edu/docs/robertson/eagle+et+al.+2011+nicholas+inst.pdf | Multi |
| 307 | No-tillage | 0.38 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |
| 308 | No-tillage | 0.29 | Rees et al. (2005) | https://doi.org/10.1016/j.geoderma.2004.12.020 | Arable |
| 309 | No-tillage | 0.15 | Gao (2018) | https://core.ac.uk/download/pdf/162124806.pdf | Multi |
| 310 | No-tillage | 0.37 | Halvorson et al. (2002) | https://doi.org/ 10.2136/sssaj2002.9060 | Arable |
| 311 | No-tillage | 0.38 | Wolff (2013) | https://winesvinesanalytics.com/features/article/123789/ | Viti/Orch |
| 312 | No-tillage | 0.23 | Paustian (2019 | https:///doi.org/10.1080/17583004.2019.1633231 | Grassland |
| 313 | No-tillage | 0.42 | Franzluebbers (2005) | https://doi.org/10.1016/j.still.2005.02.012 | Multi |
| 314 | No-tillage | 0.14 | VandenBygaart et al. (2010) | https://doi.org/10.2136/sssaj2010.0099 | Multi |
| 315 | No-tillage | 1.20 | Molina et al. (2017) | http://dx.doi.org/10.1590/1678-992x-2015-0487 | Vegetable |
| 316 | No-tillage | 0.33 | Zaher et al. (2013) | https://doi.org/10.1016/j.agsy.2013.08.004 | Arable |
| 317 | No-tillage | 0.45 | Birdsey (2002) | https://doi.org/10.1201/9781420032277.ch25 | Viti/Orch |
| 318 | No-tillage | -0.05 | Seddaiu et al. (2013) | https://doi.org/10.1016/j.agee.2013.01.002 | Viti/Orch |
| 319 | No-tillage | 1.24 | Diaz-Ravina (2005) | http://dx.doi.org/10.1016/j.agee.2016.09.011 | Arable |
| 320 | No-tillage | 0.24 | Virto (2012) | https://doi.org/10.1016/j.agee.2013.02.003 | Multi |
| 321 | No-tillage | 0.31 | Angers (2008) | https://doi.org/10.1007/s10533-011-9600-4 | Multi |

| | | | | | |
|---|---|---|---|---|---|
| 322 | No-tillage | 0.58 | Gonzalez-Sanchez (2012) | https://doi.org/10.2136/sssaj2007.0342 | Multi |
| 323 | No-tillage | 0.48 | West and Post (2002) | https://doi.org/10.1016/j.still.2012.03.001 | Multi |
| 324 | No-tillage | 0.20 | Alvarez (2005) | https://doi.org/10.2136/sssaj2002.1930 | Multi |
| 325 | No-tillage | 1.91 | Zehetner (2015) | https://doi.org/10.1111/sum.12204 | Viti/Orch |
| 326 | No-tillage | 0.07 | Machado et al. (2001) | https://doi.org/10.1016/j.agee.2016.09.011 | Arable |
| 327 | No-tillage | 0.05 | Machado et al. (2001) | https://doi.org/ 10.1023/A:1013331805519 | Multi |
| 328 | No-tillage | 0.24 | Thomas et al. (2007) | https://doi.org/ 10.1023/A:1013331805519 | Multi |
| 329 | No-tillage | 0.22 | Calegari et al. (2008) | https://doi.org/10.1016/j.still.2006.08.005 | Multi |
| 330 | No-tillage | 2.14 | Acharya et al. (1998) | https://doi.org/10.2134/agronj2007.0121er | Multi |
| 331 | No-tillage | 0.16 | Sisti et al. (2004) | https://doi.org/10.1016/S0167-1987(98)00030-0 | Arable |
| 332 | No-tillage | 0.56 | Balota et al. (2004) | https://doi.org/10.1016/j.still.2003.08.007 | Arable |
| 333 | No-tillage | 0.11 | Govaerts et al. (2007) | https://doi.org/10.1016/j.still.2003.12.003 | Multi |
| 334 | No-tillage | 0.16 | Smith et al. (2000) | https://doi.org/10.1016/j.still.2006.07.013 | Arable |
| 335 | No-tillage | 0.95 | Hernanz (2002) | https://doi.org/10.1186/1750-0680-6-11 | Viti/Orch |
| 336 | Cover crop & Legume cover crop | 1.13 | Diekow et al. (2005) | https://doi.org/10.1016/j.still.2004.03.006 | Arable |
| 337 | Cover crop & Legume cover crop | 1.27 | Maillard (2016) | https://doi.org/10.1016/j.agee.2016.09.011 | Arable |
| 338 | Cover crop & No-tillage | 0.20 | Lal et al. (1997) | Soil Properties and their Management for Carbon Sequestration (book) | Multi |
| 339 | Cover crop & No-tillage | 0.53 | Franzluebbers (2005) | https://doi.org/10.1016/j.still.2005.02.012 | Multi |
| 340 | Cover crop & No-tillage | 0.59 | De Gryze (2008) | http://www.panna.org/sites/default/files/CEC-500-2008-039.PDF | Multi |
| 341 | Cover crop & No-tillage | 0.67 | VandenBygaart et al. (2008) | https://cdnsciencepub.com/doi/pdf/10.4141/CJSS07015 | Multi |
| 342 | Cover crop & No-tillage | 4.05 | Roldan et al. (2003) | https://doi.org/10.1016/S0167-1987(03)00051-5D61 | Arable |

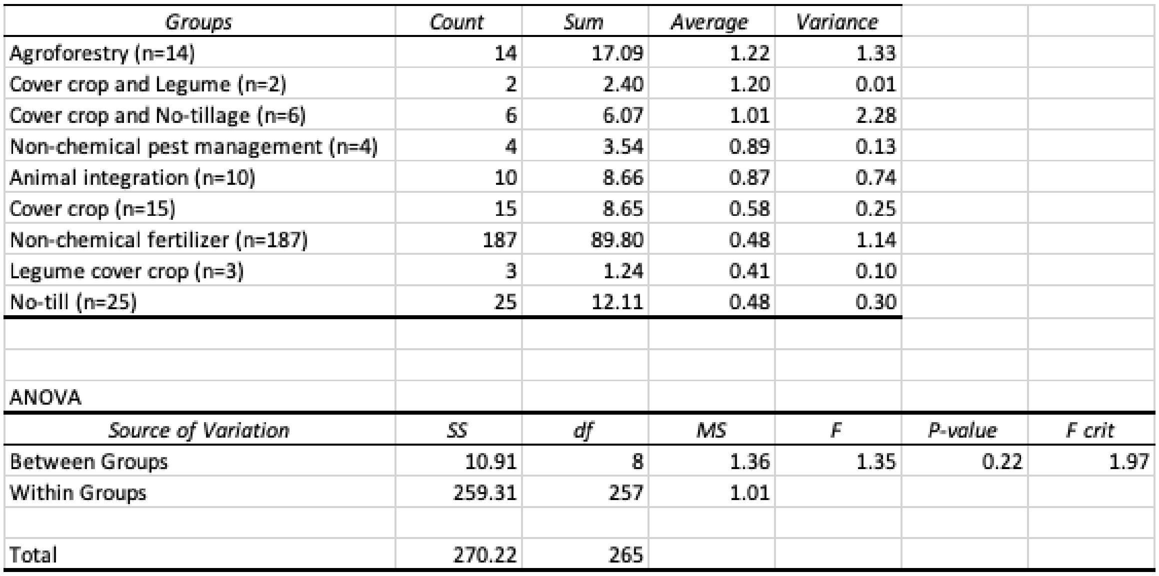
| | | | | | |
|---|---|---|---|---|---|
| 343 | Cover crop & No-tillage | 0.03 | Madari et al. (2005) | https://doi.org/10.1016/j.still.2004.06.002 | Arable |
| 344 | Cover crop & No-tillage | 0.45 | Novara et al. (2019) | https://doi.org/10.2136/sssaj2000.6451815x | Viti/Orch |
| 345 | Cover crop & No-tillage | 2.40 | Garcia-Diaz et al. (2018) | https://doi.org/10.1016/j.scitotenv.2018.10.247 | Viti/Orch |

## Ancillary Appendix 2

## Statistical Analyses of Practice C Sequestration Potential

For arable land uses, the null hypothesis was that the practice sample means of all soil regenerative practices would all be equal. Running a single-factor ANOVA, the F-value was smaller than the F-critical value for the alpha level selected (0.1), so I failed to reject the null hypothesis and assume that the means of the practices are not significantly different. The P-value was also greater than the alpha level of 0.1 selected, further indicating that the sample means are all statistically equal (Table 16).

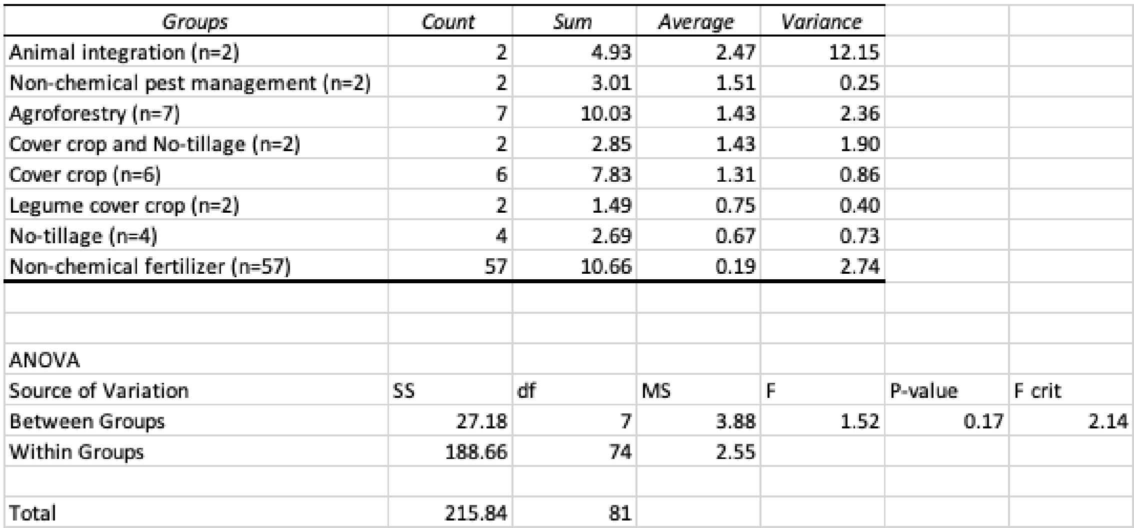
Table. 16. Single-factor ANOVA: impact of practices on arable cropland.



| *Groups* | *Count* | *Sum* | *Average* | *Variance* | | |
|---|---|---|---|---|---|---|
| Agroforestry (n=14) | 14 | 17.09 | 1.22 | 1.33 | | |
| Cover crop and Legume (n=2) | 2 | 2.40 | 1.20 | 0.01 | | |
| Cover crop and No-tillage (n=6) | 6 | 6.07 | 1.01 | 2.28 | | |
| Non-chemical pest management (n=4) | 4 | 3.54 | 0.89 | 0.13 | | |
| Animal integration (n=10) | 10 | 8.66 | 0.87 | 0.74 | | |
| Cover crop (n=15) | 15 | 8.65 | 0.58 | 0.25 | | |
| Non-chemical fertilizer (n=187) | 187 | 89.80 | 0.48 | 1.14 | | |
| Legume cover crop (n=3) | 3 | 1.24 | 0.41 | 0.10 | | |
| No-till (n=25) | 25 | 12.11 | 0.48 | 0.30 | | |
| | | | | | | |
| | | | | | | |
| ANOVA | | | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
| Between Groups | 10.91 | 8 | 1.36 | 1.35 | 0.22 | 1.97 |
| Within Groups | 259.31 | 257 | 1.01 | | | |
| | | | | | | |
| Total | 270.22 | 265 | | | | |

For woody perennial land uses, a single-factor ANOVA (Table 17) analysis of the soil organic C sequestration potential of regenerative practices indicated an F-value smaller than the F-critical value for the alpha level selected (0.1), so I failed to reject the null hypothesis and assumed that the means are statistically equal, meaning that there is no statistical difference between them. The P-value also being higher than the alpha level selected, I failed to reject the null hypothesis that the sample means are all equal.

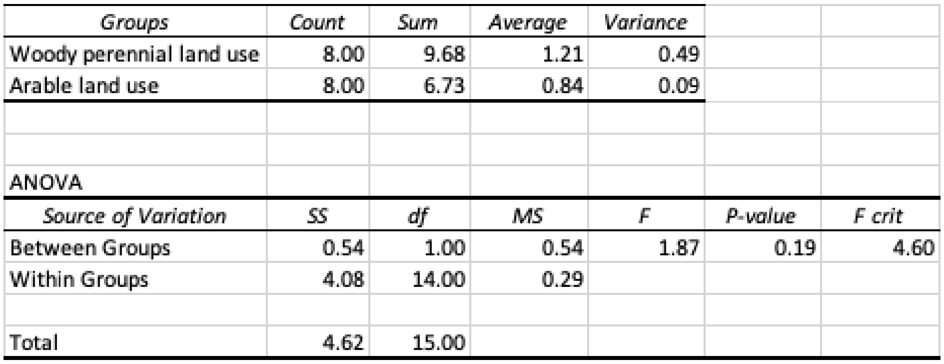
Table 17. Single-factor ANOVA: impact of practices on woody perennial cropland.



| *Groups* | *Count* | *Sum* | *Average* | *Variance* | | |
|---|---|---|---|---|---|---|
| Animal integration (n=2) | 2 | 4.93 | 2.47 | 12.15 | | |
| Non-chemical pest management (n=2) | 2 | 3.01 | 1.51 | 0.25 | | |
| Agroforestry (n=7) | 7 | 10.03 | 1.43 | 2.36 | | |
| Cover crop and No-tillage (n=2) | 2 | 2.85 | 1.43 | 1.90 | | |
| Cover crop (n=6) | 6 | 7.83 | 1.31 | 0.86 | | |
| Legume cover crop (n=2) | 2 | 1.49 | 0.75 | 0.40 | | |
| No-tillage (n=4) | 4 | 2.69 | 0.67 | 0.73 | | |
| Non-chemical fertilizer (n=57) | 57 | 10.66 | 0.19 | 2.74 | | |
| | | | | | | |
| | | | | | | |
| ANOVA | | | | | | |
| Source of Variation | SS | df | MS | F | P-value | F crit |
| Between Groups | 27.18 | 7 | 3.88 | 1.52 | 0.17 | 2.14 |
| Within Groups | 188.66 | 74 | 2.55 | | | |
| | | | | | | |
| Total | 215.84 | 81 | | | | |

Comparing the means of the practices across woody perennial and arable land use, the null hypothesis was that the means would be equal. Running a single-factor ANOVA, the F-value was smaller than the F-critical value for the alpha level selected (0.1), so I failed to reject the null hypothesis and assume that the means for practice impact between woody perennial and arable land use are not significantly different. The P-value was also greater than the alpha level of 0.1 selected, further indicating that the sample means are statistically equal (Table 18).

Table 18. Single-factor ANOVA: mean practice impact, woody perennial vs arable



| *Groups* | *Count* | *Sum* | *Average* | *Variance* | | |
|---|---|---|---|---|---|---|
| Woody perennial land use | 8.00 | 9.68 | 1.21 | 0.49 | | |
| Arable land use | 8.00 | 6.73 | 0.84 | 0.09 | | |
| | | | | | | |
| | | | | | | |
| ANOVA | | | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
| Between Groups | 0.54 | 1.00 | 0.54 | 1.87 | 0.19 | 4.60 |
| Within Groups | 4.08 | 14.00 | 0.29 | | | |
| | | | | | | |
| Total | 4.62 | 15.00 | | | | |