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CLIMATE-SMART & SUSTAINABLE VITICULTURE IN THE WESTERN CAPE, SOUTH AFRICA

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Context

Sustainability requires the full acknowledgement of a variety of social, environmental, and economic aspects and their balanced interaction. The practical application of this demanding challenge is becoming the business impetus of the 21st century. However, navigating the transformation requires a well-informed dashboard. For sustainable wine production all steps of the value creation have to be addressed, from grape production in the vineyards, vinification, bottling, packaging materials, and transport to the final customer. This report focuses on the vineyards where sustainable water usage, the enhancement of biodiversity, efficient fertilizer usage from sustainable sources, low greenhouse emissions, and low environmental toxicity are obvious environmental aspects to be considered. Social considerations include, among many others, human toxicity and safe work environments. The overarching claim for economic sustainability can be summarised as equitable remuneration for all involved in the value creation in combination with long-term financial viability.

At the onset of this project in 2017, key elements of sustainability in South African vineyards were neither broadly implemented nor adequately analysed. This report seeks to objectively expand our understanding of how best to advance environmental and social objectives. In doing so, we considered future climate change impacts, which will shape grape production in the upcoming decades. In fact, while the production potential of South African vineyards has already been limited by water availability, the projected increase in water scarcity will put additional strain on the agricultural sector, but also on other human activities and the natural ecosystems. Therefore, we argue that adapting to the expected changes is of utmost importance to the South African wine industry and has to be integrated in any sectoral or individual sustainability strategy.

Goals

Our interdisciplinary research project based on an on-farm trial addresses the following questions for vineyards in the Western Cape:

1. Do winter cover crops, a key measure to increase biodiversity and reduce herbicide applications, reduce yields?
2. What is the effect of a mulch cover on yield and main soil parameters?
3. How can human toxicity and environmental toxicity be reduced while effectively protecting the crop?
4. What is the Carbon Footprint of South African wine grapes and what are effective mitigation options?
5. What is the water usage of wine grapes and what are the related effects on the ecosystem and human activities (Water Footprint Assessment)?

Key finding 1

Regarding the effects of winter cover crops on grape yield, we distinguished between the termination of cover crops in early spring and in late spring. Thereby, we attempted to capture possible differences in prolonged transpiration of the cover crops in spring and resulting competition for vines at the onset of their phenological development. While we could not detect a statistically significant decrease in yield attributable to early or late termination of the cover crops, we found one significant increase for cover crops terminated in early spring. The control group was treated with herbicides within the working rows and in the undervine area.

Key finding 2 We found a statistically significant increase in wine grape yield for three out of four wood mulch treatments. This is a very exciting finding given the dire need to adapt to the changing climate. Considering the scarcity of mulching material such as straw, we recommend opting for sources with no or limited competitions with other use paths. In our case, we applied wood mulch with no clear dedicated use path, originating from the Working for Water project. We highly recommend scaling up this measure upon availability of sustainable sources of mulching material.

The median soil moisture in the top soil layer (0-15 cm) was roughly double in wood mulch treatments.

Key finding 3 Based on our findings there is a great potential to reduce the environmental and human toxicity on domestic wine farms: Within one year, synthetic insecticides, potentially highly detrimental to the health of farmworkers, farmers and people living in the agricultural region, could be replaced by 'natural enemies'. These are predatory insect species targeting the pest species. We highly recommend scaling up this measure upon availability of sustainable sources of mulching material. In addition to reducing human and environmental toxicity, diesel usage related to the application of insecticides as well as resource usage related to their production would be avoided. We highly recommend scaling up this measure upon availability of sustainable sources of mulching material.

Full-surface application of herbicides is unsustainable for several reasons. We found that herbicide usage was reduced by up to 70% following the establishment of a winter cover crop. However, this measure may require additional machinery and skills as well as financial resources for seeds, equipment, and labour.

Key finding 4 Compared to other important wine growing nations, South African wine grapes from irrigated vineyards have a very high Carbon Footprint. Per kg wine grapes 0,46 kg CO_2e were emitted.

With a contribution of approximately 50% greenhouse gas emissions from electricity used for irrigation were the emission hotspot. Therefore, the most effective mitigation options relate to solar-powered irrigation and energy efficient irrigation equipment.

Key finding 5 Our Water Footprint Assessment was based on two methods. First, we calculated the Water Productivity as a key indicator to measure the output of the farm, such as yield, against the water inputs required for production. The median Water Productivity amounts to 10.55 kg wine grapes produced per m^3 water from both irrigation and precipitation.

Second, we estimated the impact of irrigation water usage on the local natural ecosystem and human activities as indicated by the AWARE indicator (Available WAter REmaining). While the world average is 1 m^3-eq/m^3 the local value amounts to an impact of 61.2 m^3-eq per m^3 water abstracted for irrigation. Consequently, there is a strong negative effect on ecosystems and human activities resulting from irrigation. Referring to the irrigation amount and the yield we found a water deficit of ~19 m^3-eq per kg wine grapes.

1 Introduction

The history of wine tells not only a story of tradition but a story of change. Over generations, wine producers have successfully navigated change to build and grow the family legacy. We argue that wine producers are now facing a new and particularly big wave of change, which is driven by rising market forces demanding sustainability, but also by the changing climate.

The impact of climate change will increasingly be felt by farmers all over the world and based on the most recent data, tangible impacts can already be measured (Jägermeyr et al., 2021). In fact, farmers in South Africa's Western Cape will be particularly affected, as already hot and dry conditions will aggravate even further and leading to higher irrigation needs. This, combined with an increasing demand for water by the expanding industry and residential areas, will fuel the pressure on already scarce water resources (Midgley et al., 2016). In this context, it is unsettling that Jägermeyer et al. (2021) highlight that declining yields attributable to the gap between water demands and water availability will materialize even sooner than previously expected.

To navigate these times of change, it is of critical importance to obtain a clear understanding of the status quo, including environmental issues and health risks currently caused by the domestic wine industry. These can be severe and not unique to the South African context by nature: previous research has identified elements of environmental and social concern ranging from water use and water quality, organic and inorganic waste streams, direct and indirect fossil energy use and resulting greenhouse gas emissions to the application of toxic herbicides, insecticides, and fungicides. Further, land use issues can amplify adverse effects on ecosystems and ecosystem services (Christ & Burrit, 2013). Further, as illustrated by research summarized by Reuter & Neumeister (2015), health risks arising from the use of toxic agrochemicals can extend from the people working and living on farms to people living in the region. Meanwhile, wine is central to the culture and the economy of the world`s wine-growing areas. Further, from the perspective of regional economic sustainability, it is important to consider relationships between wine and tourism. Consequently, a decline of the domestic wine industry should be expected to adversely impact the tourism industry in the Western Cape Province.

The purpose of the Climate-smart and Sustainable Viticulture project is to identify and evaluate measures feasible for scale-up in South African vineyards, adhering to the requirements of sustainability as a holistic framework for production and consumption while recognizing and anticipating the changing climatic conditions ahead.

2 Sustainable and climate-smart viticulture: a definition

Sustainable wine is based on a systemic approach, encompassing environmental, social, and economic elements. Furthermore, this approach acknowledges that while the single aspects of sustainability can be distinguished on a conceptual level, they are closely intertwined in reality (Ponstein & Gemmrich, 2021). As explained by Ponstein & Gemmrich (2021) sustainable wine draws on the principles of sustainable production agreed upon on by the United Nations in 1992: sustainability encompasses environmental, social and economic elements. This was based on the understanding that humanity "stands at a defining moment in history" and has to give equal weight to economic efficiency, social justice and the protection of the natural ecosystems as the only feasible basis on which to proceed in the 21st century (United Nations, 1992). Sustainable viticulture concerns the grape production stage of the wine value chain, underlying the same principles than illustrated by Ponstein & Gemmrich (2021). Therefore, we propose the following definition:

Sustainable viticulture *concerns the grape production stage of the wine value chain and relies on a systemic approach, encompassing environmental, social, and economic elements; acknowledging that while the single aspects of sustainability can be distinguished on a conceptual level, they are closely intertwined in reality.*

Climate-smart viticulture *aims at higher resilience and improved productivity in a changing climate as well as minimizing greenhouse gas emissions from wine grape production.*

We derive this definition for viticulture from the generalizable claim made by Klytchnikova et al. (2015): "Meeting the rising demand for food and ending hunger and food insecurity requires a climate-smart food system that improves agricultural productivity, has greater resilience to climate change and lowers greenhouse gas emissions." Klytchnikova et al., 2015, p.4.

From our point of view, the concepts of sustainable viticulture and climate-smart viticulture have a very strong overlap in South Africa. While sustainable viticulture requires the full acknowledgement of a variety of social, environmental, and economic aspects and their balanced interaction, climate-smart viticulture has an emphasis on adapting to climate change impacts while minimizing the greenhouse gas emissions from grape production. With climate change impacts becoming increasingly tangible, it is becoming obvious to decision makers that climate-smart business models will be an integral part of a sustainable future for companies and sectors. However, the transformation to get from here to there is a challenging task.

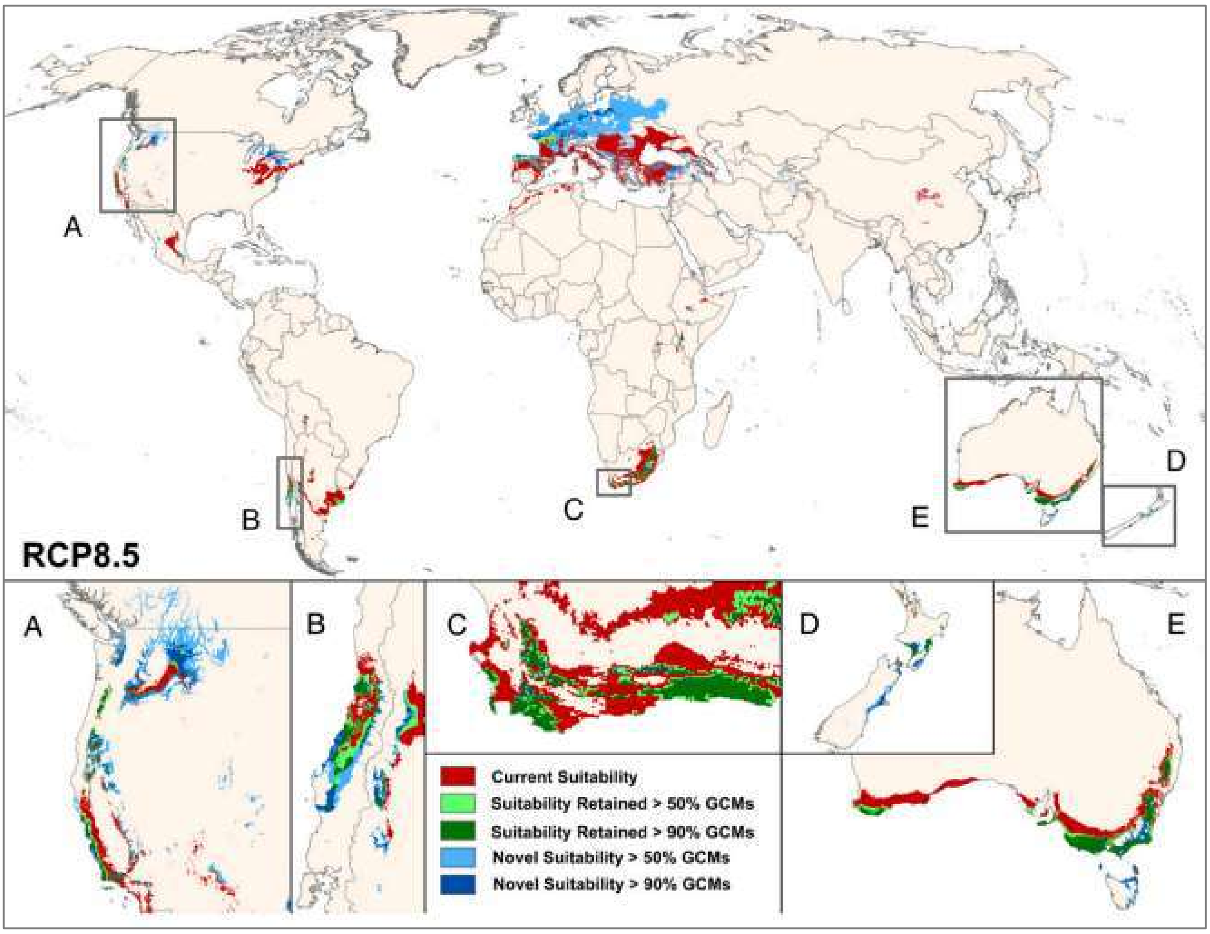
3 Problem setting

3.1 Climate change affects South African wine production

Dramatic weather events – partially attributed to a changing climate –such as the extreme drought in the Western Cape, have catapulted the severity of climate change impacts into the consciousness of the general public. On May 22nd 2017 Western Cape Premier Helen Zille declared the province a disaster area given the most severe drought in 113 years.

While not entirely caused by climate change, severe droughts are becoming more likely, which means that they are expected to occur more frequently (IPCC, 2018). The drought dated back to 2015, which was the first of three years in a row with rainfall below the 20-80 percentile range. Besides drastic measures to curb the water usage of households, the hospitality sector and industry, the allocation of water for the agriculture sector was cut by an average of 60% for 2017-2018 (WWF, 2018). Yield losses were a common consequence for the agricultural sector. Furthermore, the tourism sector was affected: Many potential guests decided against spending their holiday in a disaster area.

The remaining carbon budget to contain global warming within 2°C by the end of the century is small and diminishing daily, as regulating mechanisms operate slowly, if they exist at all. Meanwhile, the global anthropogenic net Greenhouse Gas (GHG) emissions would have to be net zero in 2055 (IPCC, 2018): All human activities may not emit more GHG emissions than can be sequestered and stored (ibid.). Importantly, a recent update of the model assessing future changes to crops related to global warming provided by NASA and PIK in November 2021 highlighted that the projected impacts on farmers should be expected earlier and will already occur within this decade (Jägermeyr et al., 2021). Analysing the future feasibility of wine grape production in the world´s main wine-growing areas by 2050 Hannah et al. (2012) concluded on the decrease of today´s productive vineyards by 25% to 75% in the RCP 8.5 scenario, which can be related to the world´s current emission pathway (Figure 1). The authors expect on a shift of vineyards towards higher elevations and areas towards the Poles to areas currently unfavourable for viticulture. Nonetheless, the net area suitable for viticulture was expected to decrease by 51% in the Winelands located in the Cape Floristic Region in South Africa (Hannah et al., 2012). Needless to say, a relocation of vineyards in the Western Cape towards the South Pole to take advantage of comparatively lower temperatures is not an option.



Change in viticulture suitability is shown between current (1961–2000) and 2050 (2041–2060) time periods, showing agreement among a 17-GCM ensemble. Areas with current suitability that decreases by mid-century are indicated in red (>50% GCM agreement). Areas with current suitability that is retained are indicated in light green (>50% GCM agreement) and dark green (>90% GCM agreement), whereas areas not suitable in the current time period but suitable in the future are shown in light blue (>50% GCM agreement) and dark blue (>90% GCM agreement). Insets: Greater detail for major wine-growing regions: California/western North America (A), Chile (B), Cape of South Africa (C), New Zealand (D), and Australia (E).

Figure 1: Global change in viticulture suitability RCP 8.5. Adopted from Hannah et al., 2012, 6908.

Wine grapes could be regarded as a proxy for other climate-sensitive crops cultivated in similar climatic conditions as these crops are likely to face similar limitations by future climates. Resulting, the existing scarcity of land suitable and available for agricultural production could be elevated as producers of citrus, apples, and almonds also seek to move production to more suitable areas. Hannah et al. (2012) and Moriondo et al. (2013) state that this relocation would result in particularly high ecological footprints, clashing with biodiversity conservation and the sustainable management of drinking water resources. Considering the unique biodiversity value of the Cape Floral Kingdom (Chapter 3.4), a relocation of vineyards and other crops would counteract the past efforts to conserve this unique biodiversity hotspot.

3.2 Exceptionally high carbon footprint of South African wines

The food sector is one of the main drivers of anthropogenic GHG emissions (IPCC, 2014). 13.5% of annual anthropogenic GHG emissions arise from agriculture (IPCC, 2007). Consequently, there is an obligation to change diets in order to realize effective resource conservation: Following the impetus to curb GHG emissions (e.g. IPCC 2007, 2014, 2018) and other environmental effects from wine production (Christ & Burrit, 2013) Van de Kamp et al. (2018) point not only towards the reduction in animal products as an obvious driver of GHGs in an individual´s diet, but also towards the replacement of wine with local tap water to effectively reduce GHG emissions related to diets, which implies that wine may appear as a dispensable luxury product in the light of the proceeding global food, water and energy crisis.

With an estimated share of 0.3% of the annual man-made GHGs (Rugani et al., 2013), the wine value chain deserves close attention to identify and manage hotspots of GHG emission sources, Ponstein et al. (2019a) illustrated the broad range of GHG emissions from the wine value chain depending on the origin of the wine and the packaging type, encompassing wines from e.g. Australia, Chile, Spain, Italy, Germany, and South Africa. Here, South African wine had a particularly high carbon footprint, especially when exported in the bottle (as opposed to bulk) (ibid.).

3.3 Increasing water scarcity in the Western Cape Province

Water availability restricts the yield potential in the Southern Cape. Conservative climate change scenarios for South Africa predict a further average increase in temperatures of up to 1.5% at the coast and 3.5% at the interior by 2030, with high regional variances. Details are presented by Vink et al. (2012) and Scholtz & Von Bormann (2016). However, these estimates may be too low given the recent conclusions of Jägermeyr et al. (2021). The authors highlighted that climate change impacts on food production will be felt earlier and within this decade. Increased temperatures will result in an increase in irrigation demand for agriculture, which is coupled with an overall increase in water use requirements of the Western Cape province. This will accelerate the already existing competition for this precious resource (Midgley et al., 2016). While the installation of irrigation equipment in vineyards is regarded as an important adaptation measure, the effectiveness thereof can be limited in drought years as water allowances should then be expected to be cut back for farmers, as seen in the drought in 2016 and 2017. As a consequence, the restoration of the soil's ability for infiltration and the conservation of soil moisture during hot summer months is of utmost strategic importance (e.g. Midgley et al., 2016).

Cover crops

In the context explained above, the use of cover crops is somewhat controversial. On the one hand, cover crops contribute to an improved infiltration, increased organic matter content, decreased soil temperatures and evaporation of soil water (amongst other positive effects), but on the other hand they increase the transpiration of soil water, which can reduce the soil water available to the main crop. (e.g. Unger & Vigil, 1998). Due to the increased transpiration, Unger & Vigil (1998) concluded that cover crops are better suited in regions with sufficient rainfall.

Different cover crops were researched in the vineyards of the Western Cape, (e.g. Fourie, 2007; Fourie, 2010; Fourie & Freitag, 2010; Fourie et al., 2015; Kruger et al., 2015). While several types of cover crops have been subject to research (ibid.), this research was largely focussed on general feasibility and weed suppression, which are important aspects. However, their effect on soil water dynamics and ultimately on the wine grape yield remain unclear.

Mulch

Soil cover provided by plants or mulch is associated with improved soil moisture and organic carbon content as well as reduced runoff and erosion in orchards in Mediterranean climates. Notably, herbicide use can even aggravate problems attributed to mechanical weed management such as low organic matter, high bulk density (compacted soil), and high runoff (Keestra et al., 2016). In an orchard in Spain, herbicide treatments caused 1.8 times more erosion than tillage and 45.5 times more erosion than cover, which included plants, litter, and chipped branches in the interrow section (ibid.). A substantial decrease of runoff and soil erosion in a vineyard with straw mulch was reported by Prosdocimi et al. (2016).

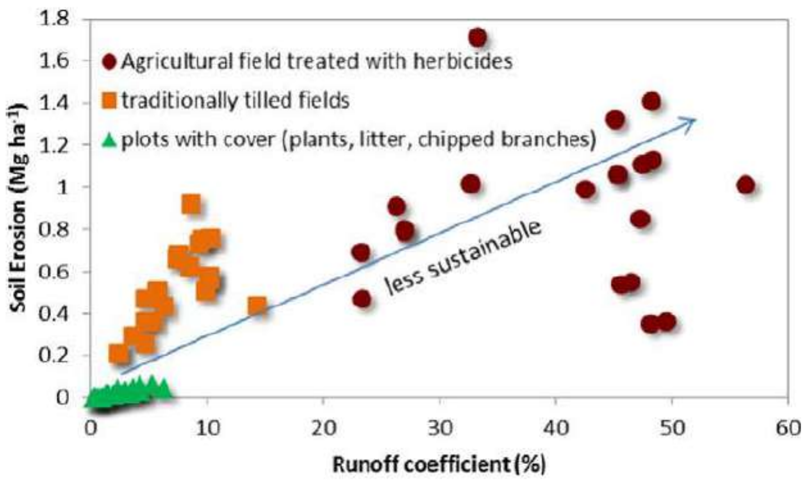


Figure 2: Effects of soil management techniques on soil water erosion. Keestra et al., 2016.

Runoff is linked to the deterioration of water quality in rivers, which may give rise to the growth of Alien vegetation in and alongside rivers. The Working for Water programme (Department of Forestry, Fisheries and the Environment, no date) aims for the improvement of water quality and the reduction of water use by alien vegetation by removing alien vegetation. Importantly, the reduction of runoff that can be achieved by sustainable farming practices directly contributes to an increase in water quality in adjacent surface waters. Therefore, the widespread adoption of cover crop-based weed control in vineyards might not only reduce the amount of herbicides applied to farmland but also contribute to an improved water quality in local rivers.

3.4 Human and environmental toxicity of current weed and pest management strategies

3.4.1 Adverse effects on human health and the environment

Pesticides (encompassing herbicides, fungicides, acaricides, and insecticides) are applied in order to control pests to protect agricultural crops. Extensive studies of their potential toxicity to biological systems highlight direct or indirect harmful effects on soil, environment, surface and ground water, natural flora and fauna and aquatic life, putting essential ecosystem services such as pollination, natural pest control, purification of water, nutrient cycling, and soil fertility at stake (e.g. Reuter & Neumeister, 2015; Rashid et al., 2010; Boutz and Stack, 1986). Meanwhile, the resilience of ecosystems to climate and weather extremes is of special importance to the Western Cape (Midgley et al. 2015). The Cape Winelands are situated in the Cape Floral Kingdom. This region is a remarkable biodiversity hotspot, providing the highest concentration of plant species, of which 70% don´t exist anywhere else in the world. However, as of 2017 only 9% of the area was formally protected. The necessity of changes in farming practices that reduce their impact on the unique biodiversity of the Cape Floral Kingdom were highlighted by the Biodiversity and Wine Initiative (BWI), established in 2004 (WWF, 2015).

Clearly, the use of pesticide and herbicide application affect people living and working in farming regions. A wide range of studies attest a negative impact on producer and community health (e.g. IRAC 2015; Bolognesi et al., 2009; Rashid et al. 2010; Eskanzi et al. 2007). The exposure to pesticides can have detrimental effects on children: Eskenazi et al. (2007) researched the impact of organophosphate-based pesticide exposure on the neurodevelopment in young Mexican-American children. They found that mothers working in the fields had higher traces of pesticides in their body system compared to the average U.S. population. Higher prenatal pesticide exposure was linked to developmental delays in children and to attention deficit hyperactivity disorder (ADHD). Further, a 5.5-point decrease in IQ scores at the age of 7 was reported for every 10-fold increase in the mother’s pesticide level during pregnancy. Transferring these findings to the South African context, the children of both farmers and farm workers are particularly vulnerable to the exposure of pesticides, with potentially life-long negative effects. Research demonstrated that risks to people´s health and the environment can extend far beyond the farm: Pesticides leach into the environment by drift in form of spray mist and dust. Further, pesticides are mobilized by vapor from evaporation and transpiration processes of the treated vegetation. They can be distributed across large distances by atmospheric movements and eventually by rain: 50% of 99 analysed pesticides (active ingredients, isomers, metabolites) were detected in rainwater in Europe (Dubus et al., 2010). Furthermore, rainfalls can wash off pesticides from plants onto and into the soil. Via leaching and drainage, an average of 1% and up to 5% can reach the groundwater by lateral and vertical infiltration (Carter 2000). From contaminated soil water or contaminated small water bodies, pesticides can infiltrate ground water, surface waters including rivers, sediments and oceans, depending on solubility and persistence (Reuter & Neumeister, 2015). In the Western Cape, pesticides were detected in the Berg River. Jackson et al. (2013) researched point sources of metal pollution and an agricultural area proved to be the point source of pollution for aluminium (Al), iron (Fe), manganese (Mg), lead (Pb), tracing back to phytosanitation. The authors point out that manganese is a major component of pesticides such as Mancozeb and Maneb, while aluminium is a component of Phosguard (ibid).

The most commonly used herbicide in the world, glyphosate (IARC, 2015), is a common weed-killer in vineyards. However, the substance was deemed to be "probably cancerogenic to humans" by the World Health Organization's cancer research institution in 2015, which is a big change given the previous evaluation as "evidence of non-carcinogenicity in humans" by the US EPA in 1991 (IARC, 2015). This is in direct contrast to the herbicide producers' claim that this substance was harmless to humans and animals. According to the IARC, "Glyphosate also caused DNA and chromosomal damage in human cells, although it gave negative results in tests using bacteria. One study in community residents reported increases in blood markers of chromosomal damage (micronuclei) after glyphosate formulations were sprayed nearby." IARC, 2015,1. In Californian wines, glyphosate residues were found in 10 out of 10 probes from various wineries in Napa Valley, Sonoma and Mendocino County, including one organic and one biodynamic vineyard. Findings ranged from 0.659 µl/l from a biodynamic vineyard to 18.74 µl/l from a conventionally managed vineyard. While the biodynamic and the organic vineyard had not been sprayed with glyphosate, residues were still found in the product, highlighting the mobility and prevalence of glyphosate in the environment (Honeycutt, 2016).

Furthermore, glyphosate was found in the blood and urine of farm workers, indicating absorption (Bolognesi et al., 2009). Moreover, glyphosate and its derivates were traced in the urine of broad parts of the population of the European Union, including 7 out of 10 residents of cities who were not directly exposed to the application of glyphosate (BUND, 2013). Moreover, even if official guidelines for “safe” pesticide usage were followed, the personal safety cannot be assured (e.g. Stehle & Schulz, 2015, Reuter & Neumeister, 2015).

To provide further information on particularly harmful pesticides that are used on domestic farmland, the list of “Highly Hazardous Pesticides” in South Africa as of 2018 is reprinted in the annex of this report. The list also contains an indication of those substances banned in Europe and subject to international conventions such as the Montreal Protocol *(Lars Neumeister,* personal communication, January 10 2022.). We thereby aspire to support the selection of active ingredients and related products by decision makers for the domestic wine, table grape, and other fruit and vegetable production in order to curb the exposure of people to health hazards.

3.4.2 Herbicide use in vineyards

At the onset of the Climate-Smart and Sustainable Viticulture project, herbicides were the key measure to control weeds underneath the vines, but also in the working rows. Application rates were at least once per year in the working row and 1-3 applications for the undervine sections. Given the maritime climate, which involves hot and dry summer months, the avoidance of competition between vines and other plants for water is of high importance. Especially in dryland farming conditions (no irrigation) the competition for water can result in a decrease in grape yield. However, considering adverse effects explained in the previous chapter, the reduction of total amounts of chemical pest control and the avoidance of toxic substances are necessary for sustainable viticulture. Besides glyphosate, paraquat dichloride is used for weed control in wine (and fruit) production in the Western Cape. Noteworthy, this is the herbicide with the highest fatality rate in the world: Thousands of people are killed by this substance every year and massive intoxications of farm workers have been reported (Neumeister, 2016). While the European Union and quality standards such as Fairtrade International or UTZ banned paraquat as a consequence (Neumeister, 2016), it is still available and used in South African vineyards. Increasing weed resistances to glyphosate have fuelled the use of paraquat (Neumeister, 2016), which can also be transferred to South African vineyards.

Table 1 provides an overview of those herbicides being approved for wine grape production according to the domestic Integrated Production of Wine scheme (IPW) in 2017, which are on the Pesticide Blacklist issued by Greenpeace (Reuter & Neumeister, 2010). The assessment includes effects on human and mammal health, environmental toxicity and environmental fate. Indicators include the Acute Reference Dose (ARfD), acute toxicity, carcinogenicity, reproduction toxicity, neurotoxicity, and endocrine disruption (Endocrine Disrupting Chemical, EDC). 71% of the herbicides that were allowed to be used in viticulture according to IPW at that time were on the Greenpeace Pesticide Blacklist, including glyphosate and paraquat. While not regarded as “best practice”; the full-surface application of glyphosate and other herbicides was found to be a common in domestic wine grape production.

Table 1: Herbicides used in viticulture in the Western Cape on Greenpeace Pesticide Blacklist (own illustration based on data from Reuter & Neumeister, 2010)

Herbicide on greenpeace Pesticide Blacklist (active ingredient)	Approval status in EU	mamal / human tocicity							environmental tocicity		environmental fate	
		ARfD*	acute toxicity	carcino-gen	reproduc-tion toxin	mutagen	neuro-toxin	EDC**	aquatic organisms	birds	bioaccu-mulative	persis-tence
amitrole	yes	-	-	-	-	-	-	x	-	-	-	-
diquat dibromide	yes	-	x	-	-	-	x	-	x	-	-	x
diuron	yes	x	-	x	x	-	-	-	-	-	-	-
Fluazifop-P-butyl	yes	x	-	-	-	-	-	-	-	-	-	-
flumioxazin	yes	-	-	-	x	-	-	-	-	-	-	-
glufosinate-ammonium	yes	x	-	-	x	-	-	-	-	-	-	-
glyphosate***	yes	-	-	x	-	-	-	-	-	-	-	-
linuron	yes	x	-	-	x	-	x	x	-	-	-	-
MCPA (4-Chlor-2-methylphenoxy)	yes	-	-	-	-	-	x	-	-	-	-	-
metazachlor	yes	-	x	x	x	x	-	x	x	x	x	x
oryzalin	yes	x	-	x	-	-	-	-	-	-	-	-
oxadiazon	yes	-	-	x	x	-	-	-	x	-	x	x
paraquat dichloride	no	x	x	-	-	-	x	-	x	-	-	x
pendimethalin	yes	-	-	-	-	-	-	-	x	-	x	x
propyzamide	yes	-	-	x	-	-	-	-	x	-	-	x
simazine	no	x	-	-	x	-	x	-	-	-	-	-
trifluralin	no	-	-	-	-	-	-	x	x	-	x	x

*ARfD = Acute Reference Dose

** EDC = Endocrine Disrupting Chemical

*** glyphosate added to blaklist in 2016

3.4.3 Insecticide usage and alternative control of insect pests

Integrated Pest Management calls for alternatives to chemical pest control whenever possible. This is particularly feasible for insect pest control, since pheromones and predatory insects (“natural enemies”) effectively protect the crop against insect pests. Aiming at avoiding adverse effects on human health and the environment, sustainable viticulture deliberately excludes synthetic insecticides. At the beginning of this trial, the control of insects was based on synthetic insecticides. In our case, mealybug was the main insect pest. The ‘natural enemies’ Anagyrus pseudococci (parasititc wasp for mealybug control) and Cryptolaemus montrouzieri (predator for mealybug control) were tested as alternatives to the synthetic insecticides “Chlorpyriphos” and “Spirotetramat”.

4 Research questions

The purpose of the Climate-Smart and Sustainable Viticulture project is to objectively expand our understanding of how best to advance environmental, social and therefore financial objectives of wine grape production while anticipating the changing climatic conditions ahead.

Our interdisciplinary research project based on an on-farm trial addresses the following questions for vineyards in the Western Cape:

1. Do winter cover crops, a key measure to increase biodiversity and reduce herbicide applications, reduce yields?
2. What is the effect of a mulch cover on yield and main soil parameters?
3. How can human toxicity and environmental toxicity be reduced while effectively protecting the crop?
4. What is the Carbon Footprint of South African wine grapes and what are effective mitigation options?
5. What is the water usage of wine grapes and what are the related effects on the ecosystem and human activities (Water Footprint Assessment)?

5 Methods

5.1 On-farm experiment

5.1.1 Location

The Climate-smart and Sustainable Viticulture Project was based on an on-farm trial in a commercial vineyard in the Perdeberg area, Western Cape Province. The vineyard with the size of 1 hectare and an average yield of 8 tons of the grape variety Cabernet Sauvignon was located close to Wellington at (33°34'15.8"S 18°53'34.5"E) (Figure 3, “Bassano trial site”). The experiment encompassed of 60 rows with 40 vines per row.

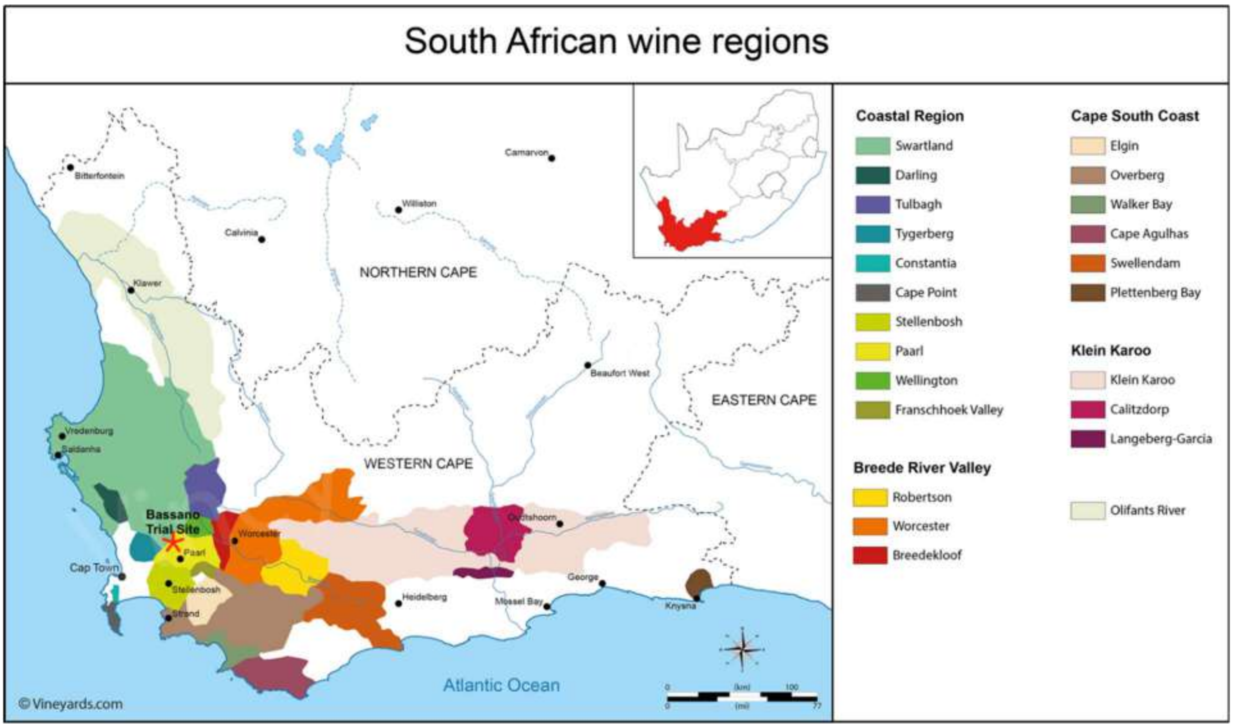


Figure 3: Wine Growing Regions in South Africa (source: vineyards.com, modified), retrieved from Russo et al., 2021.

Following Clewer & Scarisbrick (2001,5) an effort was made to ensure that the soil texture is homogenous based on an electromagnetic soil map facilitated by Dr. Albert Strever (Stellenbosch University) as well as Berno Greyling and Jacobus Els (Revolute Systems).

5.1.2 Duration

The split-plot was established in the second quarter of 2017. The last sampling activity was in March 2021 and concerned the wine grape yield of the 2020/2021 season.

5.1.3 Experimental design: split plot

Standard principles of experimental design encompass replication, randomisation, and blocking (Federer, 1955, in Piepho et al., 2011), which apply to on-farm experiments (Piepho et al., 2011). In on-station research, experimental units are generally small plots, while experimental units in on-farm experiments may use long strips, parts of a field, or even whole fields. If classical randomised designs are employed and a single measured value is obtained per experimental unit, standard statistical procedures can also be applied to on-farm experiments (Piepho et al., 2011). Without replication and randomization, a statistical proof of a hypothesis is not possible (ibid.). The minimum replication rate is three times, while the statistical advantage added is smaller with each additional replicate. On on-farm trials, there typically are fewer treatments per trial, and experimental error variance as well as plot sizes tend to be larger (Fielding & Riley, 1998). However, well-designed experiments on farms with sufficient replication may reach precision comparable to on-station experiments (Piepho et al., 2011).

This on-farm experiment was based on a split-plot design. It included four replications, exceeding the minimum number of replications needed for statistical analysis. There were 40 sampling areas of which 8 were attributed to the control and 4 each to the different treatments, thereby creating a more robust base for the control. As depicted in Figure 7, one treatment plot extended over four vine rows and three working rows and was subdivided into two subplots (hence the name “split-plot”. There was one sampling area per subplot, as marked in green colour in Figure 7. The sampling zone extended over 7 meters times 1.7 meters and had an area of 11.9 square meters. The sampling areas marked blue relate to the location of the soil moisture and temperature probes (Figure 7).

The treatments and the control were randomly assigned to the blocks. The trial encompasses three test factors, which are described below. The block design can be expressed as (A*B)/C.

A: Fertilizer, a=2

- Synthetic fertilizer, SF
- Organic fertilizer, OF

B: Termination of cover crops (date), b=2

- Early termination of cover crop ET (4 weeks prior to T2), T1
- Standard termination of cover crop, at same time of herbicide application, T2

C: Cover crop, c=2

- Cover crop, C1
- Cover crop and addition of wood mulch, C2

Control:

- Control: No cover crop, bare soil, herbicide application and tillage (Figure 4).

All undervine sections were treated with herbicide where the mulch cover was not present or too thin to suppress the weeds.

Table 2 summarizes the different treatment combinations.

Table 2: Treatment combinations

#	Description
1	ynthetic fertilizer, early termination, no mulch
2	Organic fertilizer, early termination, no mulch
3	Synthetic fertilizer, early termination, mulch
4	Organic fertilizer, early termination, mulch
5	Synthetic fertilizer, standard termination, no mulch
6	Organic fertilizer, standard termination, no mulch
7	Synthetic fertilizer, standard termination, mulch
8	Organic fertilizer, standard termination, mulch
9	Control: Bare soil throughout the year

The Figures 4, 5, and 6 provide photos of the different treatments.

Figure 4: Left: Cover crop, no mulch, early termination. Centre: control row with bare soil after full-surface herbicide treatment. Yield and soil samples were taken from the middle row.

Figure 5: Left: cover crop, late termination. Centre: cover crop, early termination after mowing. Right: control rows with bare soil.

Figure 6: Left: control row with bare soil. Centre: Winter cover crop, organic fertilizer, standard termination, no mulch.

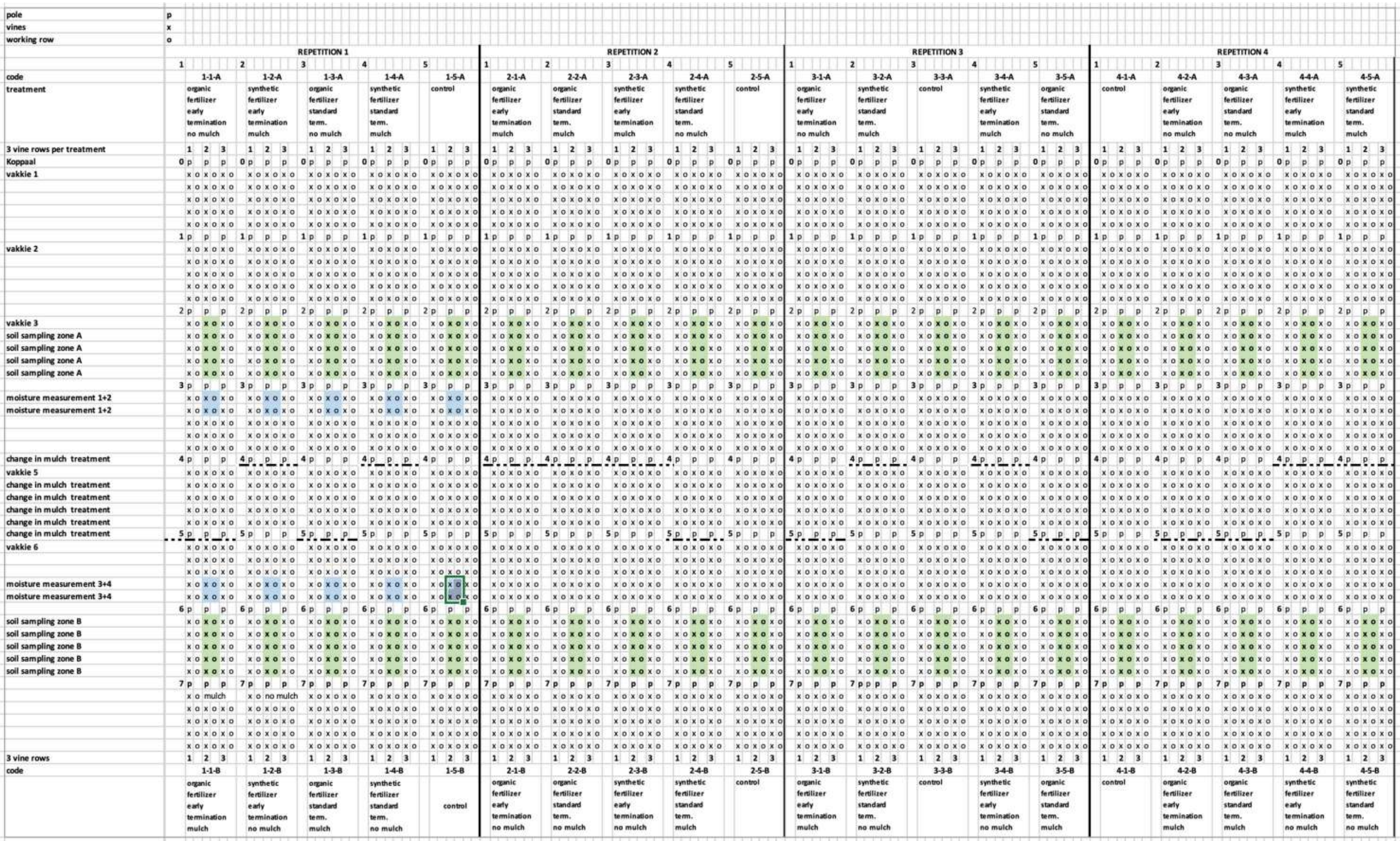


Figure 7: Layout of split-plot and sampling areas. Green: soil sampling area. blue: soil moisture and temperature sensors. Vakkie (Afrikaans) = distance between two poles

5.1.4 Test factors / treatments

5.1.4.1 Fertilizer

The domestic standard fertilizer recommendation for cover crop (in addition to the vines) at the onset of the trial were 50 kg LAN (14 kg N) for grains, while it was 50 kg LAN (14 kg N) and 50 kg phosphate (10.5 kg P2O5) if legumes were part of the mixture of cover crop species. During the growing season, two doses thereof were recommended, which would result in a recommended synthetic fertilizer addition to cover crops of 100 kg LAN (28 kg N) and 100 kg super phosphate (21 kg P) per year. We propose that this recommendation is excessive and does not only impose extra cost to the wine producers but environmental burdens from e.g. nutrient leaching and greenhouse gas emissions. This is a direct contradiction between this business-as-usual approach and the goals of sustainable and climate-smart farming, where the goal is to use resources effectively and efficiently with minimal side-effects. Moreover, this business-as-usual approach imposes avoidable cost on wine producers.

Nevertheless, given that the trial was established on a vineyard that received full-surface herbicide application in previous years and that the soil had a very low organic matter and nutrient content, so it seemed somewhat plausible to support the growth of the cover crop at the beginning. We compared the BAU (business as ususal) recommendation for cover crop provided by synthetic fertilizer against providing one organic fertilizer dose in the first year and then proceeding with a mix of grains and legumes, but without further external fertilizer additions.

Trialled fertilizer types and doses:

The trial includes two fertilizer types, namely synthetic and organic fertilizer.

a) Synthetic fertilizer

These plots received 50 kg LAN (14 kg N) per hectare.

b) Organic fertilizer

In year 1 (2017) organic fertilizer (Talborne Organics) at 14 kg N/ha was applied.

From year 2 onwards lupines were part of the cover crop in this treatment and no further fertilizer was applied.

5.1.4.2 Termination dates of cover crop growth in spring

A well-established cover crop can consume several litres of water per day and per m². This may negatively impact the water balance of the vineyard in spring and can lead to water stress of the vine. Therefore, it may be preferable to stop the growth of the cover crop in early spring to preserve soil moisture. The cover crops can be rolled flat using a heavy crimper. This no-till measure is practiced by trials led by Johann Strauss (Department for Agriculture), who reported a great success of this measure, as long as the crimper is heavy enough. From his visual observation, the mulch layer created by the rolled cover crops conserved soil moisture very well. In the first year, the rolling flat of cover crops was trialled by means of a heavy tire, which was pulled through the working row. This might be a low-cost option to farmers, not requiring the investment into additional equipment. However, this measure was not successful in this trial as the cover crop continued and therefore, the cover crop was mulched.

a) Standard termination of winter cover crop

The first date is the **traditional timing** of the termination of cover crops in spring, coinciding with herbicide application at the onset of the phenological development of the vines. This timing shifted throughout the project duration due to the varying weather in the seasons.

b) Early termination of winter cover crop

The timing for the "early termination" treatment of the cover crop was approximately 4-6 weeks prior to the "standard termination". Thereby, the experiment captured possible impacts on yield attributable to the termination date of the winter cover crop.

5.1.4.3 Cover crop species

Cover crop species diversity enhances soil life and improves the resilience of the stand. Crop species must be selected carefully to suit the given the climatic and soil conditions. Concerning cover crop species suitable for vineyards in the Western Cape, several studies were available (Fourie, 2007; Fourie, 2010; Fourie & Freitag, 2010; Fourie et al., 2015; Kruger et al., 2015). In addition, the project could draw on several experts, namely Johann Strauss (Landcare/Department of Agriculture), Jaco Kellermann (Barenbrug), Prof. Dr. Gemmrich (Deutsches Institut für Nachhaltige Entwicklung, DINE), Rolf Fox (Weinbauschule Weinsberg, Fox, 2000), and Heinie Nel (Perdeberg Cellar).

In theory, a wide range of species would be available for use as cover crops in South African vineyards. In praxis, this is limited by the physical availability of the seed, establishment cost and practical barriers such as seed size and variations in germination requirements. Since this trial aimed at reducing the existing practical implementation barriers the choice of the cover crop species used in this trial was based on the following features:

- The **performance** of species as winter cover crops has been approved under **local conditions**;
- **Manageable seed size for the existing equipment**: the seed sizes are homogenous and large enough to be handled well by farmers without suitable machinery;
- Homogenous **seeding depth** requirements suitable for simple seeding equipment;
- Fast and similar phenological development;
- Mix of shallow and deep rooting plants;
- **Tolerance** to a broad spectrum of soil texture and pH-levels;
- Strong **biomass development** to generate mulch;
- **Balanced C:N** ratio of the mulch material;
- Good **availability** of seeds and **low cost** of the seed mix.

As a result, we chose oats, barley and lupines as cover crops.

5.1.4.4 Wood mulch from the Working for Water programme

Common sources of mulch are straw and wood chips, but the amount of mulch material in the Western Cape is limited. The scarcity of straw mulch was aggravated in drought years: in the drought years 2015/2016, there was virtually no straw available for mulch, as this resource had been allocated to animal husbandry. Wood mulch is a limited resource, but can be available thanks to the Working for Water programme (Department of Forestry, Fisheries and the Environment, no date), which removes invasive tree species such as pine and eucalypt from riverbeds and wetlands. This results in substantial accumulations of wood biomass, with no clearly defined use paths. The wood mulch was provided by Landcare (Department of Agriculture, Western Cape). It consisted of Eucalypt (red gum) wood and originated from the Berg River, where Eucalypt trees were removed as part of the Working for Water programme. Prior to application, the mulch was tested for heavy metal contents at the local laboratory Bemlab. With heavy metal contents well below the South African and the European thresholds for compost, the application to vineyards was considered safe.

A mulch cover of coarse wood chips with the thickness of 10 cm was applied to the working rows and the undervine section in August 2017 (Figure 8). The mulch layer was topped up in the undervine section in August 2019 to maintain the thickness of the mulch layer there throughout the experiment (Figure 9).

Figure 8: Wood mulch present in the undervine section.

Figure 9: Reapplication of wood mulch in undervine section in August 2018.

5.1.5 Soil samples

The soil samples were taken within each of the 40 dedicated sampling areas. Per sampling area, three samples were pulled at random areas within the respective sampling zone and mixed in a bucket. From this mixed soil, one sample was provided for laboratory analysis. The samples were kept in a temperature-controlled environment.

The soil was extracted with hollow metal poles made of hardened steel, as displayed by Figure 10. These poles were inserted into the soil with a hammer. This type of equipment was also functional in dry conditions when the soil was very hard.

Figure 10: Soil sampling equipment

5.1.6 Yield samples

Harvesting data were available for 2018, 2019, 2020, and 2021 and sampling took place at the beginning of March in the respective years. To obtain sampling data, the grapes of the vines within the sampling zone, hence to the left and to the right of the working row where the soil samples were taken, were harvested. These grapes were weighted in the crates on a field scale (Figure 11). There were 10 vines per sampling zone.

Figure 11: Yield sampling with field scale

5.2 Difference-in-Differences analysis

For investigating the impact of the treatments described previously, we analysed how soil components (Ph, P, NO_3, NH_4, C, Organic matter) and grape yield changed over time using a Difference-in-Differences (DID) approach (Lechner, 2010). This method allows for the assessment of the impacts on these parameters specifically arising from the treatments. Importantly, changes in these same parameters attributable to external factors such as rainfall, temperatures or irrigation, which naturally occurred in the time span of 2017 – 2021 and affected all treatments and the control equally, are subtracted from the observed effects. Thereby, these time trends (weather, irrigation, etc.) influencing the soil parameters and grape yield independently of the treatments are left out of the analysis. Therefore, the DID method enables us to focus on the direct effects from the treatments and to provide an estimate of the intervention effect (Figure 12).

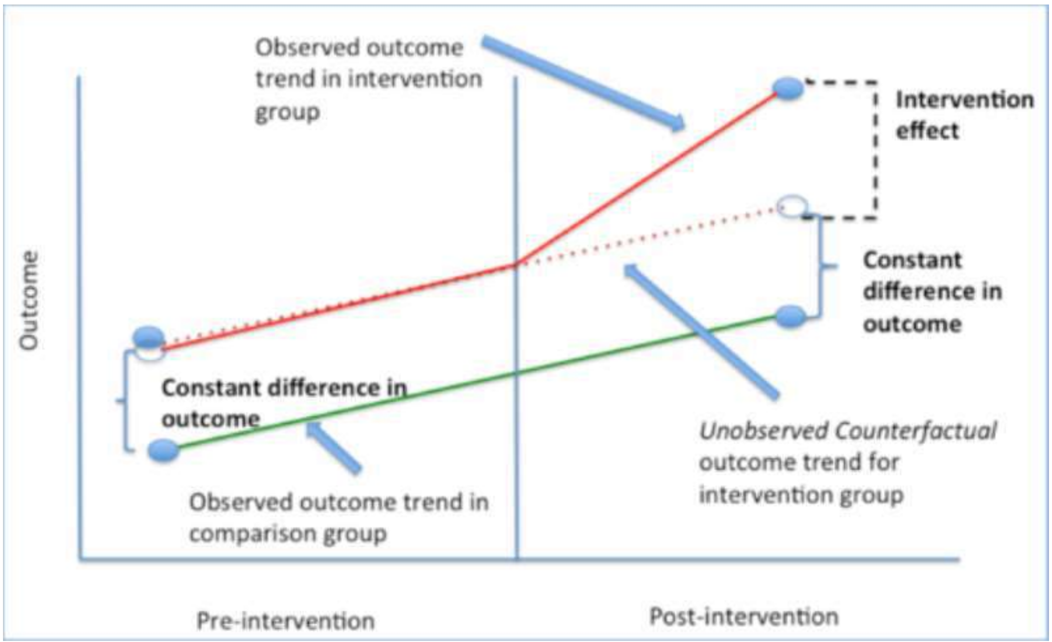


Figure 12: Difference-in-Differences estimation, graphical explanation. Source: Columbia University Mailman School of Public Health (2019).

According to Lechner (2010, p. 168), if the treated and the nontreated units 'are subject to the same time trends, and if the treatment has had no effect in the pre-treatment period, then an estimate of the "effect" of the treatment in a period in which it is known to have none, can be used to remove the effect of confounding factors to which a comparison of post-treatment outcomes of treated and nontreated may be subject to'. This effect can be estimated by using the following formula:

$$\beta = (\bar{Y}_B^T - \bar{Y}_A^T) - (\bar{Y}_B^C - \bar{Y}_A^C)$$

where β is the estimated effect, $\bar{Y}_B^T$ is the average outcome of the treated unites before the treatment, $\bar{Y}_A^T$ is the average outcome of the treated unites after the treatment, $\bar{Y}_B^C$ is the average outcome of the controls (nontreated) unites before the treatment, $\bar{Y}_A^C$ is the average outcome of the controls (nontreated) unites after the treatment. For an exhaustive description of the DID statistical assumptions refer to Blundell & Costa Dias (2009) and Imbens & Wooldridge (2009). However, the application of DID to the "*Climate-smart and Sustainable Viticulture Project*" in the Western Cape, South Africa has some limitations. In particular: First, the DID methodology assumes the presence of a baseline period in which no units have been treated. Unfortunately, we do not have data referring to such a period for all of the single treated subplots. However, since we are interested in observing the change arising from the different treatments in the following years, we use 2017 as pre-intervention period, even if it would technically be more appropriate to call it as "*intervention period*". 2018, 2019, and 2020 are post-intervention periods.

5.3 Life Cycle Assessment

5.3.1 Methods and data

Based on this on-farm experiment, we provided the first Life Cycle Assessment (LCA) on different domestic wine grape farming practices, all suitable for commercial production in South Africa. Thereby, this work contributes to the transparency of environmental effects arising from the domestic wine industry and the effectiveness of realistic changes as described by the scenarios, published as Russo et al., 2021. The study encompasses eight scenarios and the Business as Usual (BAU). The following ReCiPe 2016 *Midpoint(H) (*Huijbregts et al., 2016) impact categories were analysed: Global Warming Potential, Terrestrial Acidification, Freshwater Eutrophication, Terrestrial Toxicity, Freshwater Toxicity, Marine Toxicity, Human Carcinogenic toxicity and Human Non-Carcinogenic Toxicity. Furthermore, two Damage Assessment categories, namely Human Health and Ecosystems, from ReCiPe 2016 *Endpoint(H)* (ibid.) were included. The toxicity assessment was based on UseTox 2.0 (Fantke et al., 2017). The results were generated using SimaPro V. 8.5 software and are based on ecoinvent V. 3.5 unit datasets. The Life Cycle Inventory is displayed in Table 3.

Concerning the evaluation of water use in viticulture, we explored the AWARE indicator (chapter 5.3.3), which is displayed in the Life Cycle Assessment highlighted above, and the Water Productivity indicator (chapter 5.4)

Table 3: Life Cycle Inventory. Adopted from Russo et al., 2021.

		Scenarios								
		Baseline	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Inputs	Unit per ha	Full surface herbicide, chemical pest mgmt. (CPM)	50% cover crop A[1], CPM	100% cover crop A, CPM	50% cover crop A, integrated pest mgmt.(IPM)	100% cover crop A, IPM	50% cover crop B[2], CPM	100% cover crop B, CPM	50% cover crop B, IPM	100% cover crop B, IPM
Inputs from Nature										
Land	ha	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water (P)	m^3/yr	2639.56	2639.56	2639.56	2639.56	2639.56	2639.56	2639.56	2639.56	2639.56
Energy content of biomass	MJ	29470.10	29470.10	29470.10	29470.10	29470.10	29470.10	29470.10	29470.10	29470.10
Inputs from Technosphere										
Diesel	L	114.75	139.25	163.75	112.25	136.75	135.88	157.00	108.88	130.00
N grapes	Kg	44.00	44.00	44.00	44.00	4.00	44.00	44.00	44.00	44.00
N cover crop	Kg	0.00	14.00	28.00	14.00	28.00	0.00	0.00	0.00	0.00
P_2O_5 grapes	Kg	4.80	4.80	4.80	4.80	4.80	4.80	4.80	4.80	4.80
P_2O_5 cover crop	Kg									
Electricity	kWh/yr	1316.86	1316.86	1316.86	1316.86	1316.86	1316.86	1316.86	1316.86	1316.86
Irrigation	m^3/yr	2520.00	2520.00	2520.00	2520.00	2520.00	2520.00	2520.00	2520.00	2520.00
Agri-chemicals Inputs										
Herbicides		*Herbicides surface factors:* • Full surface =1 (100% of the herbicide dosage) • 50% Cover crop = 0.65 (a 35% herbicide reduction of the dosage in Baseline Scenario)								

		• 100% Cover crop = 0.3 (a 70% herbicide reduction of the dosage in Baseline Scenario)								
Therbuthylazine	g/ha (a.i.)[3]	2100.00	1312.50	525.00	1312.50	525.00	1312.50	525.00	1312.50	525.00
Glyphosate	g/ha (a.i.)	540.00	337.50	135.00	337.50	135.00	337.50	135.00	337.50	135.00
Paraquat	g/ha (a.i.)	750.00	468.75	187.50	468.75	187.50	468.75	187.50	468.75	187.50
Insecticides										
Spirotetramat (movento)	g/ha (a.i.)	25.20	25.20	25.20	0.00	0.00	25.20	25.20	0.00	0.00
Chlorpyriphos	g/ha (a.i.)	466.38	466.38	466.38	0.00	0.00	466.38	466.38	0.00	0.00
Fungicides		50% of sprays are Sulphur; 50% are a systemic fungicide either Mancozeb or Spiroxamine, thus a 50% Mancozeb and 50% Spiroxamine was assumed; 6-8 fungicide applications per season which are adopted to the weather conditions. Sulphur is used in dry conditions while a systemic fungicide is applied in moist weather conditions. Last spray usually at end of December.								
Mancozeb	g/ha (a.i.)	980.00	980.00	980.00	980.00	980.00	980.00	980.00	980.00	980.00
Spiroxamine	g/ha (a.i.)	229.69	229.69	229.69	229.69	229.69	229.69	229.69	229.69	229.69
Sulphur	g/ha (a.i.)	2205.00	2205.00	2205.00	2205.00	2205.00	2205.00	2205.00	2205.00	2205.00
Penconazole	g/ha (a.i.)	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13

[1]Cover crop A: grains only (barley or oats), [2]Grains and legumes combined (barley or oats with lupines), [3]gram of active ingredient per hectare.

5.3.2 Water data sources

For the analysis related to water, two main sources of data were used in this report:

1. Data from the farmer on the Irrigation pattern for 2017-2018, 2018-2019, 2019-2020 and 2020-2021 growing seasons;
2. Weather data was measured on-site with a weather station provided by Ileaf, which could be accessed online at http://ileaf.co.za. The data from the on-site Weather Station included: Temperature, Rainfall, Wind speed, Wind directions, Relative humidity, Dewpoint, Radiation, Sun hours, Leaf wetness, Evapotranspiration, Absolute Humidity, and Specific humidity.

Homogeneity of data at the level of time resolution

- The start of the season was determined at the beginning of the 14th week of the respective year, until the 13th week of the subsequent year.
- Data on irrigation were provided at a weekly resolution (mm of water per week) and worked out to be on a daily resolution (knowing that irrigation is at 2 mm*hr);
- Data from the weather station could be retrieved at different time resolutions - hourly, daily, weekly. The data was retrieved at both daily and weekly intervals. The recordings were available for the trial site “Bassano” from July 31 2017 onwards, following the installation of the weather station on site. From the beginning of the 2017-2018 season at March 27 2017 and July 30 2017, weather station data for “Perdeberg” from the same provider was used as a proxy. This station was located within a radius of 10 km.

Precipitation

The precipitation data were retrieved from the South Africa Weather Service (https://www.weathersa.co.za/home/weathermaps) and from the on-site weather station (https://ileafweather.com/) and are listed below.

- 2017-2018: 200-300 mm, 264.5 mm;
- 2018-2019: 300-500 mm, 477.8 mm;
- 2019-2020: 300-500mm, 347.6 mm;
- 2020-2021: 300-500 mm, 432.8 mm.

The following table summarises the water usage at the trial site and distinguishes between precipitation and irrigation water. The 2017-2018 harvest season has been affected by the drought hitting the region in 2016-2018, registering ~2,600 m^3*ha*yr less water available compared to the following harvesting years. The harvesting years of 2018-2019, 2019-2020, and 2020-2021 registered ~30% of more water available compared to the 2017-2018 harvesting year. The harvesting season irrigation pattern was the same for 2018-2019, 2019-2020 and 2020-2021, thus the difference in the overall water balance is caused by the measured annual variability in precipitation.

Notably, the 2017-2018 season was the driest in the presented time-span. Drastic reductions in rainfall lead to harshest water restrictions to avoid "day zero", the day where water supply to households would no longer be possible due to zero water available.

Table 4: Precipitation and irrigation data and total water supply

Harvest Year	Total water supply (m^3 *ha*yr)	Precipitation (m^3 *ha*yr) and contribution to water supply (%)	Irrigation (m^3 *ha*yr) and contribution to water supply (%)
2017-2018[2]	6,005	2,645 (44.05%)	3,360 (55.95%)
2018-2019	8,858	4,778 (53.94%)	4,080 (46.06%)
2019-2020	8,2756.8	3,476.8 (42.01%)	4,800 (57.99%)
2020-2021	9,128	4,328 (47.41%)	4,800 (52.59%)

[1] W.r.t. HY: with respect to harvest year 2017-2018, i.e. the harvest in March 2018.

[2] Precipitation data was retrieved for the "Perdeberg" weather station until July 30st. From July 31st onwards, data was provided by the weather station at the "Bassano" trial site.

5.3.3 AWARE (Available WAter REmaining)

The following section was adopted from Russo et al., 2021, p. 1380.

Consumptive water was calculated using the ReCiPe 2016 Midpoint(H) method, while a Water Footprint Assessment (WFA) was done separately to account for impacts on the local environment, assessing the stress faced by the water resources within the area of the trial site. ReCiPe 2016 supports the accounting of the amount of water needed but does not provide an impact assessment, which was added using the AWARE method (Boulay et al., 2018). A water footprint is a measure of how much water a process or service requires and the resulting direct and indirect environmental impacts, measuring local water scarcity, typically expressed volumetrically. This number can be interpreted as the amount of water downstream users are lacking as a function of water consumption on site and thus, the WFA depicts the pressure exerted by an activity (wine grape farming in our case) on the watershed area. The AWARE method illustrates the use-to-resource ratio, namely Demand-To-Availability, and indicates the relative impact on downstream water users compared to the average water consumption in the world. Thereby, we assess the relative Available WAter REmaining per area in a specific watershed after the demand of humans and aquatic ecosystems has been met (Boulay et al., 2018) and apply a local and national characterization factor *[…]*.

The main challenge in a WFA is to get the most representative data for the specific local conditions. Global data is generally more readily available to cover background processes to the life cycle, however, the relevance of the results based on global data may be lower compared to local data, since the latter are more relevant to and representative of the local situation. Local input data on irrigation water were retrieved from personal communication with local experts, whereas water inputs attributable to precipitation was calculated using rainfall data gathered from the South African Weather Services and two local weather stations (Perdeberg and Nooitgedacht). Water used in upstream ancillary processes was calculated based on ecoinvent.

5.4 Water Productivity

In their analysis of water use indicators at farm scale, Prochnow et al. (2012) explored the "Farm Water Productivity" as a key indicator to measure the output of the farm, such as yield, against the water inputs required for production. This indicator combines hydrological factors with precipitation, evaporation from plants and soil, and different sources of irrigation water (ibid.)

In our simplified approach, the WP was calculated as the ratio between the annual grape yield [kg fresh fruit per sampling area] obtained at harvest and the water applied (WA) by irrigation [m^3 per m^2 of sampling area] for each sampling area. The sampling area refers to the stretch between to vineyard poles, covering the approximate area of 7 meters x 1.7 meters = 11.9 square meters. A visualization is provided by Figure 7. Water from precipitation ('green water') and irrigation ('blue water' or 'technical water') was reported separately. This approach is also referred to as 'crop per drop' approach and is illustrated in equation below:

$$WP = \frac{yield}{WA}\left[\frac{Kg}{m^3}\right]$$

The data quantifying the different water sources were scaled down from $m^3*ha*yr$ to m^3*m^2*yr to allow for a calculation per sampling area.

5.5 Soil moisture & soil temperature data

Aside from weather data and irrigation water amounts detailed in chapter 5.3.2, the trial generated soil moisture and soil temperature data. 40 soil moisture probes were installed in the area of the first repetition. While sensors were installed at 15cm, 30 cm and 80 cm in the undervine section, the working row received sensors at 15 cm and 30 cm depths. This setup is depicted in Figure 13, while their location within the on-farm trial can be observed in Figure 7: Layout of split-plot and sampling areas. Here, the locations of the soil moisture sensors are marked in a blue colour. Raw Data from the SM150T sensors were retrieved in the Delta Link proprietary format (dt6) and converted into the csv format by the Delta Link software used for data gathering at trial site. The raw data was converted into % soil moisture according to the calibration performed at the beginning of the recording period. Temperature data was recorded for sensors in 15 cm depth only.

Data was recorded at 30 minutes intervals. The recording started in week 42 in October 2017 and continued until the removal of the sensors on 23rd October 2020. Unfortunately, the majority of soil sensors failed over time. Further, data was lost for the second quarter of 2020. During the lockdown severe travel restrictions due to Covid19 imposed non-essential travels beyond 5 km of radius from dwelling during the months March-June 2020. Data was lost because maintenance intervals of the water loggers for battery checks and data gatherings were disrupted. Following the limitations described above, the analysis was based on a weekly resolution of primary data which was then aggregated to an annual level. Due to lack of data, we could not compare the soil moisture recordings in the areas with treatments against the control.

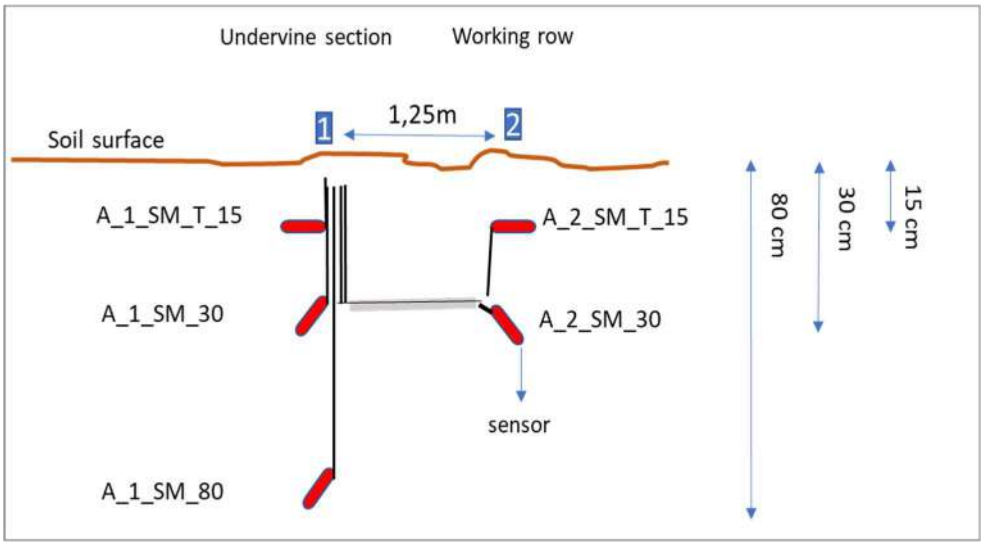


Figure 13: Location of soil sensors in undervine section and working row.

6 Results and discussion

6.1 Changes in precipitation, irrigation and wine grape yield

The average (median) wine grape yield per vine for the harvest of 2018, 2019, 2020, and 2021 was 2,48 ranging between 2.267 kg (2021) and 2.806 kg (2020). The minimum and maximum values in the table below illustrate the substantial variability of the yield: the variance ranges from 18% in 2018 to 29% in 2019 and 2020, with an average variance of 28% throughout the trial. Given the rather short study duration, we cannot be sure to which extent the treatments increased the overall variability (expressed as variance). Statistically significant changes attributable to the treatments relative to the control were determined by Difference-in-Difference analysis (cf. Chapter 5.2), presented in the subsequent chapters.

Table 5: Wine grape yield 2018-2021

Variable	2018	2019	2020	2021	Total duration
		kg grapes per vine			
Median	2.489	2.297	2.806	2.267	2.478
Min	1.688	1.205	1.888	1.608	1.205
Max	3.794	4.007	5.289	4.182	5.289
Standard deviation	0.455	0.661	0.809	0.571	0.689
Variance	18%	29%	29%	25%	28%

Compared to the 2017-2018 harvest year, while total water supply increased by 48% in 2018-2019, the yield decreased by 8%. In 2019-2020 the total water applied to the vineyard increased by 38% compared to the same reference period, and the yield rose by 13%. Comparing 2020-2021 to the reference period of 2017-2018, the total water applied increased by 52% while the yield dropped 9%. Variations in precipitation, irrigation, and the resulting total water supply as well as the median wine grape yield (cf. chapter 5.1) are displayed in the table below.

Table 6: Variation in precipitation, irrigation, total water supply and median wine grape yield

Harvest year	precipitation	irrigation	total water supply	variation in grape yield[1]
Variation with respect to harvest year 2017/2018 (harvest in March 2018)				
2018-2019	80.64%	21.43%	48%	-8%
2019-2020	17.41%	42.86%	38%	13%
2020-2021	48.41%	42.86%	52%	-9%

[1] The median wine grape yield is based on all treatments and the control.

Looking at the evolving patterns, precipitation and total water supply are positively linked. On the other hand, irrigation and yield diverge. As shown in Table 6, yields did not always increase in accordance with higher volumes of irrigation. Considering that the average contribution of irrigation water to the total water supply ranged from 46% in 2018-2019 and 58% in 2019-2020 with no related increase in yield, we suggest that there may be room for reducing the irrigation without negatively affecting yield. Another possible interpretation is that irrigation water supply is one of many conditions affecting yield which are subject to high annual variability, such as wind and rain during flowering. In general, wine grape production is subject to very high degrees (Rugani et al., 2013, Ferrara and de Feo, 2018, Ponstein et al., 2019a, b) of temporal variability, hence variability between harvest years (Huijbregts, 1998, Björklund, 2002). The degree of temporal variability of the vineyard assessed in this trial is unknown to us and can only be understood over longer time periods. Therefore, we recommend future research to obtain more data over longer time periods to come to more robust conclusions.

6.2 The effect of cover crops and mulch on wine grape yield

We aimed at contributing to a better understanding to what extend differences in termination dates of cover crop growth in spring relate to wine grape yield. Possibly, yield is affected due to differences in the transpiration of soil water arising from the cover crop depending on whether their growth was stopped very early in spring (early termination) or could continue until bud break (late termination). This could result in a competing for soil moisture between the cover crop and the vines, potentially dismissing cover crops as a sustainability measure feasible in the changing climate.

Over the project period, we found several statistically significant changes attributable to the cover crop and mulch treatments. Based on our data, there was no statistically significant decrease in yield attributable to cover crops or mulch. On the contrary, over the four-year period, we found one (out of four) statistically significant increase in the wine grape yield for cover crops. Then, for mulch we found three out of four statistically significant increases in yield, again comparing the yield in March 2018 and in March 2021 (see Table 7). All other treatments provided a positive trend, but a trend is not a statistically significant change. In brief, these were the treatments with the significant increases:

- Organic fertilizer, standard termination, no mulch: 12.57 percentage points;
- Synthetic fertilizer, standard termination, mulch: 10.82 percentage points;
- Organic fertilizer, standard termination, mulch: 10.28 percentage points;
- Synthetic fertilizer, early termination, mulch: 6.95 percentage points.

Comparing 2018 against 2019, we found no significant changes but an overall positive trend. Notably, trends are not statistically significant. Comparing 2018 against 2020, the positive trend became more pronounced and one yield increase was statistically significantly. Based on our data, statistically significant effects on yield materialized only after several subsequent years of applying the treatments.

Interestingly, we could not detect a clear pattern between early and late termination of cover crops. On the other hand, while there was no statistically decrease in yield related to cover crops, the one cover crop treatment leading to a statistically significant *increase* in yield was terminated late. One could conclude that the timing of the termination of cover crop does not matter. However, we recommend to be careful with generalizing this result into a broadly applicable conclusion. It has to be considered that this result was obtained in an irrigated vineyard, where drip irrigation supplied approximately 50% of the annual water sources (cf. chapter 5.3.2), counteracting potential additional soil water reductions by cover crops. Therefore, we conclude that the soil water usage of the cover crop played a minor role in the context of an irrigated vineyard. These effects should be investigated further and extended to non-irrigated (dryland) vineyards.

Therefore, keeping in mind the methodological limitations explained earlier (chapter 5.2), we provide two conclusions. First, we conclude on a positive effect on yield resulting from mulch application in an irrigated vineyard: three out of four treatments that included wood chip mulch resulted in a significantly higher yield over the four-year period. Here, the statistically significant positive effect on yield materialized only after several subsequent years of mulch and cover crop treatment. We suggest that – given the availability of sustainable sources – the mulching of vineyards should be scaled-up as a sustainability measure increasing the resilience to climate change impacts. Second, we conclude that, as long as irrigation water sources are available, a winter cover crop does not result in decreased yields and is a suitable sustainability measure.

We highly recommend to extend the analysis to a longer time frame to obtain more robust data.

Table 7 illustrates the effects of cover crops and mulch on wine grape yield as percentage points while Table 8 displays the results as kg per vine.

Table 7: Effects of cover crops and mulch on wine grape yield (percentage points)

	Treatment	2018 vs. 2019	2018 vs. 2020	2018 vs. 2021
		results expressed as percentage points		
1	organic fertilizer early termination no mulch	0.81	6.05	4.88
2	synthetic fertilizer early termination mulch	-1.16	8.49	4.39
3	organic fertilizer standard term. no mulch	3.15	6.62	**12.57****
4	synthetic fertilizer standard term. mulch	-2.76	4.46	**10.82****
5	control			
6	organic fertilizer early termination mulch	1.15	**10.72***	5.87
7	organic fertilizer standard term. mulch	1.69	6.87	**10.28****
8	synthetic fertilizer standard term. no mulch	2.83	1.20	3.01
9	synthetic fertilizer early termination no mulch	9.85	7.43	**6.95***
	Treatment		2019 vs. 2020	2019 vs. 2021
1	organic fertilizer early termination no mulch		569	4.42
2	synthetic fertilizer early termination mulch		11.,37	6.54
3	organic fertilizer standard term. no mulch		3.46	9.40
4	synthetic fertilizer standard term. mulch		9.35	**17.58****
5	control			
6	organic fertilizer early termination mulch		10.25	5.05
7	organic fertilizer standard term. mulch		5.45	9.04
8	synthetic fertilizer standard term. no mulch		-1.64	0.18
9	synthetic fertilizer early termination no mulch		-1.90	-2.28
	Treatment			2020 vs. 2021
1	organic fertilizer early termination no mulch			-0.92
2	synthetic fertilizer early termination mulch			-3.01
3	organic fertilizer standard term. no mulch			4.61
4	synthetic fertilizer standard term. mulch			5.28
5	control			
6	organic fertilizer early termination mulch			-3.34
7	organic fertilizer standard term. mulch			2.63
8	synthetic fertilizer standard term. no mulch			1.68
9	synthetic fertilizer early termination no mulch			-0.36

Results in bold and highlighted in grey are statistically significant: * 10% significance; ** 5% significance; *** 1% significance.

Table 8: Effects of cover crops and mulch on wine grape yield (kg per vine)

	Treatment	2018 vs. 2019	2018 vs. 2020	2018 vs. 2021
		deviation in kg grapes per vine compared to the control		
1	organic fertilizer early termination no mulch	0.0795	0.5923	0.4778
2	synthetic fertilizer early termination mulch	-0.1213	0.8871	0.4591
3	organic fertilizer standard term. no mulch	0.2783	0.5851	**1.1111****
4	synthetic fertilizer standard term. mulch	-0.2584	0.4183	**1.0138****
5	control			
6	organic fertilizer early termination mulch	0.1122	**1.0430***	0.5710
7	organic fertilizer standard term. mulch	0.1582	0.6414	**0.9601****
8	synthetic fertilizer standard term. no mulch	0.2621	0.1114	0.2785
9	synthetic fertilizer early termination no mulch	0.9116	0.6874	**0.6430***
	Treatment		2019 vs. 2020	2019 vs. 2021
1	organic fertilizer early termination no mulch		0.5128	0.3983
2	synthetic fertilizer early termination mulch		1.0084	0.5804
3	organic fertilizer standard term. no mulch		0.3068	0.8328
4	synthetic fertilizer standard term. mulch		0.6768	**1.2723****
5	control			
6	organic fertilizer early termination mulch		0.9308	0.4588
7	organic fertilizer standard term. mulch		0.4832	0.8019
8	synthetic fertilizer standard term. no mulch		-0.1507	0.0164
9	synthetic fertilizer early termination no mulch		-0.2242	-0.2686
	Treatment			2020 vs. 2021
1	organic fertilizer early termination no mulch			-0.1146
2	synthetic fertilizer early termination mulch			-0.4280
3	organic fertilizer standard term. no mulch			0.5260
4	synthetic fertilizer standard term. mulch			0.5955
5	control			
6	organic fertilizer early termination mulch			-0.4720
7	organic fertilizer standard term. mulch			0.3187
8	synthetic fertilizer standard term. no mulch			0.1670
9	synthetic fertilizer early termination no mulch			-0.0444

Results in bold and highlighted in grey are statistically significant: * 10% significance; ** 5% significance; *** 1% significance.

6.3 The effect of cover crops and mulch on key soil parameters

The Difference in Difference analysis was applied to several soil parameters (P, PH, C, Organic Matter, NO_3 as N, NH_4 as N) for the beginning of the project in June 2017 as "*intervention period*" against October 2020 as post-intervention period (Table 9). Comparing these seasons, we assume that changes from our treatments on parameters such as PH, Organic Matter and Soil Carbon are less influenced by seasonality and the comparison of the very beginning and the end of the project provides valuable and transferrable insights. The results presented below illustrate the *changes* of the parameters attributable to the treatments and compared against the control.

Table 9: Difference-in-difference analysis results for selected soil parameters (2017 – 2020)

June 2017 - October 2020		P (Bray 1)	Ph (KCl)	C (Walkley Black)	Organic matter	NO_3 as N (KCl)	NH_4 as N (KCl)
Treatment		mg/kg	dimension -less	percentag e points	percentag e points	mg/kg	mg/kg
1	organic fertilizer early term. no mulch	-11.375 (23.917)	0.083 (0.276)	**0.200 (0.102)***	**0.344 (0.175)***	0.494 (3.257)	0.439 (0.755)
2	synthetic fertilizer early term. mulch	**-22.625 (13.243)***	-0.257 (0.225)	**0.320 (0.126)****	**0.550 (0.217)****	-0.100 (2.991)	**0.899 (0.491)***
3	organic fertilizer standard term. no mulch	-6.375 (19.645)	-0.065 (0.267)	**0.530 (0.147)*****	**0.912 (0.253)*****	3.380 (2.768)	**1.113 (0.455)****
4	synthetic fertilizer standard term. mulch	-20.375 (16.611)	-0.017 (0.215)	0.180 (0.112)	0.310 (0.193)	3.389 (2.706)	0.062 (0.538)
5	control						
6	organic fertilizer early term. mulch	-15.875 (12.329)	0.120 (0.226)	0.070 (0.092)	0.120 (0.158)	1.476 (2.852)	0.136 (0.499)
7	organic fertilizer standard term. mulch	-14.625 (12.184)	-0.100 (0.246)	0.070 (0.096)	0.120 (0.166)	4.425 (2.739)	0.802 (0.535)
8	synthetic fertilizer standard term. no mulch	-6.875 (14.021)	0.152 (0.205)	0.150 (0.101)	0.258 (0.173)	1.710 (2.984)	-0.532 (0.460)
9	synthetic fertilizer early term. no mulch	-9.375 (12.999)	-0.010 (0.221)	0.100 (0.117)	0.172 (0.201)	0.206 (2.823)	0.015 (0.501)

Results in bold and highlighted in grey are statistically significant: * 10% significance; ** 5% significance; *** 1% significance.

Soil carbon and organic matter

We found an observable trend of an increase in soil carbon and organic matter compared to the control for all treatments, while for three out of eight treatments the increase was statistically significant. Two out of four treatments with organic fertilizer provided a statistically significant increase in soil carbon and organic matter, while one out of four treatments with synthetic fertilizer treatments also provided a significant increase in these soil parameters. Given the fact that the presence of organic matter is increased by both a winter cover crop and a mulch application and that the control treatment resulted in minimizing biomass apart from the vines by full-surface herbicide applications, the overall increase in both organic matter and soil carbon is plausible. Since soil carbon is a parameter that changes very slowly, we highly recommend to extend the observation period to obtain a solid understanding to which extent and in which time horizons organic carbon can be stored in domestic vineyards previously depleted of organic matter.

- “Organic fertilizer early termination no mulch”
  - Increases the presence of Carbon (C) by 0.200 percentage points;
  - Increases the presence of Organic material by 0.344 percentage points.
- “Synthetic fertilizer early termination mulch”
  - Decreases the presence of P by 22.625 mg/kg;
  - Increases the presence of Carbon (C) by 0.320 percentage points;
  - Increases the presence of Organic material by 0.550 percentage points;
  - Increases the presence of NH_4 as N by 0.899 mg/kg.
- “Organic fertilizer standard termination no mulch”:
  - Increases the presence of Carbon (C) by 0.530 percentage points;
  - Increases the presence of Organic material by 0.912 percentage points;
  - Increases the presence of NH_4 as N by 1.113 mg/kg.

All other outcome variables did not display statistically significant results.

Fertilizer recommendations for cover crop

While there was one statistically significant reduction in P for the treatment “synthetic fertilizer, early termination, mulch”, there was a trend for decreased levels of P for both, synthetic fertilizer and organic fertilizer. We attribute this trend to the removal of the cover crop as fodder by the farmer. We could not observe a statistically significant pattern with regards to soil parameters including NH_3-N and NO_4-N concentrations when comparing the ‘synthetic fertilizer’ and ‘organic fertilizer’ treatments, but an overall trend for an increase in these nutrients regardless of the type of fertilizer. Concerning the fertilizer recommendations for cover crops in domestic vineyards, we conclude that the application of Nitrogen fertilizer to cover crop has no benefit. Due to the negative trend of P levels regardless of the fertilizer type and cover-crop combination, we suggest to consider the replacement of synthetic fertilization of wine grapes with local organic fertilizer sources such as manure or compost, which naturally include a broad spectrum of macro- and micro nutrients. Utilizing these waste streams of other production processes would support the closing of regional nutrient cycle as opposed to introducing additional nutrients. Further, we could not observe parallel patterns when comparing changes in wine grape yield and changes in selected soil parameters, which underscores our suggestion of changing current fertilizer application recommendations for cover crops to zero.

6.4 The effect of cover crops and mulch on soil moisture

We compared soil moisture (soil volumetric water content, vol%) for mulch, no mulch, early termination of cover crops and late termination of cover crops at 15 cm, 30 cm, and 80 cm depth. The median soil moisture content measured for the soil under mulch cover far exceeded the soil moisture without a mulch cover throughout the trial (Table 10). This difference was particularly pronounced at 15 cm depth, where the moisture content of mulch treatments. While the median soil moisture contents of the soil sensors at 15 cm depth recorded 19.25% of soil moisture for mulch cover, it was only 9.99% for areas without mulch. Therefore, mulch resulted in an increase in soil moisture content of 9.26 volume %, providing an increase by 93% compared to the absence of mulch cover. This divergence between mulch and no mulch treatments decreased with depth: at 30 cm, the mulch treatment recorded 22.13 vol%, resulting in a delta of only 4.50 vol% (26%). The median soil moisture readings at 80 cm depth resulted in 23.33 vol% for mulch and 22.69 vol% for areas without mulch, providing a small difference of only 0.65 vol% (3%). The minimum and maximum soil moisture % values did not show a large convergence, indicating that extreme states were reached under both mulch and no mulch conditions. Considering the findings described above, we attribute the difference to a slower drying up of the soil under mulch cover, effectively conserving soil moisture.

Comparing soil moisture for cover crops terminated early and cover crop terminated late in spring (Table 11), we did not find a divergence comparable to the effect of mulch illustrated above. In fact, the median soil moisture content across the project duration showed very small differences.

The low soil moisture values for the season of 2017 – 2018 (low compared to the total project duration as well as the 2018-2019 and 2019-202 season) were attributable to the decreased amount of rainfall, as described in chapter 5.3.2.

Considering the statistically significant increases in yield in three out of four cases, as illustrated in chapter 6.2, we propose that the conservation of soil moisture by mulch is a main reason for the positive effect on wine grape yield.

Our findings were compared to Schorr (2003), who explored the effects of different soil treatments, including mulch, on soil water and yield, amongst other parameters over a five-year period. In his doctoral thesis, he also found a statistically significant increase in yield for the mulch treatment, compared to ploughed soil and mulched grass in the working rows. However, while effects of the soil treatment of yield were significant for the mulch treatment, he could not observe a statistically significant change in soil moisture for any treatment. Both findings confirm our observations.

Table 10: Aggregated soil moisture recordings according to sensors depth and mulch cover versus no mulch

		Mulch			No mulch		
		15 cm	30 cm	80 cm	15 cm	30 cm	80 cm
Soil volumetric water content // % soil moisture (Vol%)							
Overall	Median	19.25	22.13	23.33	9.99	17.54	22.68
	Max	69.72	69.13	69.26	69.91	69.91	39.32
	Min	0.16	0.51	5.26	0.33	0.70	0.88
	Stdv	12.45	9.96	7.14	9.30	13.58	6.25
	Var	64.65%	44.99%	30.59%	93.08%	77.44%	27.55%
2017-2018	Median	10.27	21.08	22.50	6.56	13.84	21.81
	Max	61.51	67.98	37.67	48.56	48.56	31.51
	Min	3.73	0.51	10.94	4.06	3.85	10.45
	Stdv	6.02	7.71	6.78	2.48	7.40	5.51
	Var	58.64%	36.56%	30.14%	37.84%	53.52%	25.28%
2018-2019	Median	19.73	24.41	22.96	11.46	18.19	23.84
	Max	35.07	48.57	42.69	69.91	69.91	38.88
	Min	0.25	1.58	5.26	1.87	2.88	9.29
	Stdv	7.68	9.13	6.61	5.61	10.93	5.96
	Var	38.92%	37.38%	28.79%	48.94%	60.12%	25.01%
2019-2020	Median	23.91	22.78	25.69	15.63	20.72	22.21
	Max	69.72	69.13	69.26	69.03	69.03	39.32
	Min	0.16	3.37	8.53	0.33	0.70	0.88
	Stdv	15.84	12.16	7.64	13.77	19.73	6.50
	Var	66.26%	53.39%	29.74%	88.10%	95.24%	29.28%

Table 11: Aggregated soil moisture recordings according to sensors depth and early versus late termination of winter cover crops.

		Early termination of cover crops			Late termination of cover crops		
		15 cm	30 cm	80 cm	15 cm	30 cm	80 cm
		Soil volumetric water content // % soil moisture (Vol%)					
Overall	Median	10.10	19.12	22.34	9.97	17.30	23.67
	Max	51.18	65.93	39.32	55.87	69.91	38.88
	Min	0.33	0.88	0.88	1.46	0.70	9.06
	Stdv	7.21	13.54	6.74	9.91	13.30	5.55
	Var	71.37%	70.82%	30.16%	99.34%	76.91%	23.46%
2017-2018	Median	6.24	9.66	17.04	6.64	15.08	23.62
	Max	51.18	25.43	48.56	15.98	48.56	31.51
	Min	4.06	3.85	10.45	4.52	6.42	13.82
	Stdv	2.62	7.49	5.61	2.34	7.19	3.70
	Var	42.04%	77.55%	32.90%	35.24%	47.65%	15.65%
2018-2019	Median	11.05	19.50	22.83	14.19	18.08	26.27
	Max	25.08	39.47	31.63	24.24	69.91	49.96
	Min	2.62	4.14	10.78	1.87	2.88	9.29
	Stdv	8.16	8.92	5.89	5.61	12.64	6.00
	Var	73.81%	45.72%	25.78%	39.51%	69.93%	22.84%
2019-2020	Median	16.39	30.78	23.04	19.36	15.69	20.32
	Max	65.93	65.93	39.32	55.87	67.91	26.99
	Min	0.33	0.88	0.88	1.46	0.70	9.06
	Stdv	16.65	19.23	7.24	14.77	17.70	4.44
	Var	101.57%	62.48%	31.42%	76.30%	112.85%	21.84%

6.5 The effect of cover crops and mulch on soil temperature

With regard to the soil temperatures at 15 cm depth, we distinguish between “mulch” and “no mulch”. The recorded average, maximum and minimum temperatures as well as the standard deviation and variance are depicted in Table 12. Notably, the mulch treatment resulted in lower median temperatures (-12%), maximum temperatures (-5%) and minimum temperatures (-36%) across the project duration. A similar pattern was observed for the single time periods. Mulch resulted in the lowest recordings of median, maximum, and minimum temperatures throughout the project and within each time period. One exception is the maximum recording for mulch in the time span of 2018-2019, which we attribute to a decreased thickness in mulch cover above one of the sensors. As described in chapter 5.1.4.4 the mulch layer was topped up in the undervine section in August 2019 to maintain the thickness of the mulch layer there throughout the experiment.

Also, the standard deviation and variance as measures for natural variability were lowest in soil treated with mulch. Therefore, the mulch cover resulted in lower temperatures and less variability, hence more stable temperatures.

Given that three out of four mulch treatments resulted in a statistically significant increase in wine grape yield, we suggest that the soil temperature moderated by the mulch cover, in combination with the higher soil moisture volumes illustrated above, have a positive effect on yields.

Table 12: The effect of winter cover crops and mulch on soil temperature at 15 cm depth, in °C

		No mulch	Mulch	Difference
		°Celsius at 15 cm depth		
Overall	Median	20.40	18.00	-12%
	Max	31.30	29.60	-5%
	Min	8.80	5.60	-36%
	Stdv	4.77	4.44	
	Var	23.38%	24.67%	
2017-2018	Median	25.73	21.45	-17%
	Max	30.20	25.00	-17%
	Min	17.20	14.50	-16%
	Stdv	3.08	2.52	
	Var	11.97%	11.75%	
2018-2019	Median	20.1	16.85	-16%
	Max	28.90	28.70	-1%
	Min	12.80	10.40	-19%
	Stdv	4.65	4.14	
	Var	23.13%	24.57%	
2019-2020	Median	19.40	15.80	-19%
	Max	31.30	29.60	-5%
	Min	12.80	8.30	-35%
	Stdv	4.02	4.50	
	Var	20.72%	28.48%	

6.6 The carbon footprint of wine grapes

The average result of the carbon footprint of wine grapes according to the inputs illustrated in Table 3 is 0.46 kg CO_2-eq/kg grape (min: 0.43, max: 0.53 kg CO_2-eq/kg grape). This finding is within the range of previous results for South African wine production when considering a fully irrigated vineyard (Russo et al., 2021).

Russo et al. (2021) explain the single elements of the carbon footprint as follows: "Irrigation inclusive of electricity contribution is mostly the same for all the Scenario and it accounts for ~50% on average. Diesel Usage accounts for an 24.2% on average of the total Global Warming Potential (GWP) across all the scenarios (ranging from 20.5 to 28.2%). Fertilisers and Agri-chemical production accounts for a ~17% on average (ranging from 15% to 22%) and this is due to the different usage amounts across the scenarios. Farming practices inclusive of fertilisers and agrochemical emission contributions account for an average 8.3% on the total Global Warming Potential (GWP) across all the Scenarios (ranging from 7.6% to 10.2%). Substances that contribute to GWP emissions are mainly fossil CO_2 which accounts for 75.4%; N_2O which accounts for about ~17%; Fossil CH_4 which accounts for a 6.2%."

The carbon footprint results were compared to those by Janse van Vuuren (2015) and Ponstein et al. (2019a) whose studies were based on the same spatial system boundaries (Russo et al., 2021). Janse van Vuuren (2015) compiled the GHG of Western Cape wine grape production, reporting an average of 0.42 kg CO_2-eq /kg grapes. Ponstein et al. (2019a) provided GHG emission data for South African wine grapes in the context of the global Finnish wine supply chain and reported an average of 0.30 kg CO_2-eq /kg grapes produced in South Africa, assuming that 85% of the domestic vineyards were irrigated.

When testing the results for robustness, Russo et al., 2021 found that the main driver of variability is the irrigation pump´s electricity requirement. This can be related to the total amount of water pumped, but also to the energy efficiency of the equipment. Therefore, using energy efficient equipment is a meaningful mitigation option. Further, the replacement of grid electricity with solar power on the level of the farm or the pump would mitigate a substantial part of the carbon footprint of wine grapes (ibid.). Furthermore, concerning sources of variability of the carbon footprint of wine, the findings of Ponstein et al. (2019b) should be considered. Here, natural variations (Björklund, 2002) of yield were a main contributor to variance. This means that declining yield increases the carbon footprint of wine grapes, while increasing yields can reduce GHG emissions on product level (Ponstein et al., 2021b). As a consequence, declining yield in South African vineyards, which are an expected consequence of progressing climate change (Hannah et al., 2012), will drive up GHG emissions of wine arising from the viticulture stage of wine production.

The sensitivity analysis of electricity inputs (Table 13) and of the irrigation water inputs (Table 14) concern the main drivers of the carbon footprint of South African wine grapes (Russo et al., 2021). In a nutshell, both the amount of irrigation water and the type of energy used for electricity generation are key elements for mitigating GHG emissions from the viticulture stage (ibid.).

The irrigation water usage in the Life Cycle Inventory informing the analysis (Table 3) was below the irrigation water usage reported by the viticulturist (Table 4), because representative industry data was sought for the Life Cycle Assessment. Considering that the irrigation volume reported by the viticulturist at the Bassano trial site was almost double the industry average in some years, and that the energy usage therefore exceeds the one assumed in this study, we highlight the possibility of a much higher carbon burden per kg wine grapes than expressed by Russo et al. (2021).

Table 13: Sensitivity analysis of electricity inputs and related GWP (Russo et al., 2021)

Scenario (all diesel and electricity inputs are for pumping)	Electricity Input (MJ to pump 1 m^3 of water)	Overall GWP (kg CO_2-eq/ kg wine grapes)	Irrigation contribution (kg CO_2-eq/ kg wine grapes)	Irrigation contribution % of the total GWP
Background dataset[1], no adaptation	D[2]: 0.252 E[3]: 0.441	0.259	0.053	20.6%
100% drip irrigation & background diesel + electricity	D: 0.252 E: 0.441	0.284	0.079	27.6%
100% drip irrigation & background electricity	E: 0.691 D:0.000	0.303	0.097	32.0%
100% drip irrigation & (Eskom) average tariff electricity (used in our analyses)	E:1.967 D:0.000	0.435	0.229	52.6%
100% drip irrigation & (Eskom) standard tariff electricity	E: 2.245 D:0.000	0.464	0.258	55.7%

[1]South African background irrigation dataset from the ecoinvent database V. 3.6, see section 2.2 for details on Water Inputs for Irrigation; [2]D: Diesel generator-based electricity; [3]E: Grid electricity.

Table 14: Sensitivity analysis of irrigation water inputs and related GWP (Russo et al., 2021)

Scenario	Water Input *(m^3 of water per 1 ha per 1 year)*	Overall GWP (kg CO_2-eq/ kg wine grapes)	Irrigation contribution (kg CO_2-eq/ kg wine grapes)	Irrigation contribution % of the total GWP
Low Irrigation	600	0.267	0.062	23.1%
Average Irrigation	2,520	0.435	0.229	52.6%
High Irrigation	3,840	0.601	0.395	65.7%

6.7 The water footprint of wine grapes (AWARE indicator)

The section below is adopted from Russo et al., 2021, pp. 1383-1386.

The water usage per 1 kg of wine grapes produced is of about 0.646 m^3/ kg of wine grapes and consists of irrigation water (0.315 m^3/ kg) measured on the farm, upstream ancillary processes not directly at farm level (0.002 m^3/ kg) and green water from precipitation (0.329 m^3/ kg) according to ReCiPe 2016 Midpoint(H). The amount of irrigation water corresponds to the average irrigation scenario as per Table 3 (2,520.00 m^3/ha/yr) for all scenarios presented in this article. The amount of abstracted water used at farm for irrigation is 0.315 m^3/1 kg wine grape represents the irrigation pattern of our trial and is based on the following expert information:

- 2 mm water per hour;
- 12 hours per week;
- ~10 weeks of irrigation until harvesting, the low to high irrigation scenario range is 5-16 weeks.

Applying the local AWARE indicator of 61.2 m^3-eq/m^3 to the irrigation water abstracted by the farm in the watershed of the Perdeberg area, the result is 19.38 m^3-eq per kg wine grapes. This is a moderate result stating that the water usage of 0.317 m^3 per kg grapes in this area relates to a water deficit of ~19 m^3-eq for human activities and the ecosystem. As a reference the world average is 1 m^3-eq/m^3. Therefore, wine production in this region clearly exacerbates the competition for already scarce water resources, also compared to other regions within the country. Applying the AWARE indicator for South Africa at country-level (40.76 m^3-eq/m^3) results in only 12.83 m^3-eq/kg, which is clearly lower than the results on the watershed level, underscoring the need to rely on the most representative data and highlighting that the wine grape production is located in a particularly water-scarce region of the country. Table 15 reports the consumptive water quantity and the Water Footprint Assessment results for the AWARE method, including the different AWARE Characterisation Factors for South Africa at the country level and at the watershed level for the trial site, allowing for a comparison between national and regional scales.

Table 15: Water Footprint Analysis based on the AWARE method for 1 kg wine grapes (Russo et al., 2021)

Water source	Water usage (m^3/kg)	Impact assessment at the country level (m^3-eq/kg)	Impact assessment at the local watershed level (m^3-eq/kg)
Total Blue Water	0.317	12.91	19.38
Irrigation	0.315	12.83	19.26
Ancillary processes	0.002	0.08	0.12
Total Green Water from precipitation	0.329		

6.8 Water Productivity

The water input from irrigation and precipitation in the years 2017-2018 (harvest in March 2018), 2018-2019 (harvest in March 2019), and 2019-2020 (harvest in March 2020) is displayed in the method section in Table 4, see chapter 5.3.2.

The average Water Productivity is 10.55 kg wine grapes produced per m³ water input from both irrigation and precipitation. Here, 42% arise from “blue water” from irrigation (WP_{blue}), translating into an average value of 4.43 kg per m³ irrigation water.

The WP for the harvest years 2018, 2019, and 2020 as well as the subdivision into WP_{blue} and WP_{green} are illustrated in the table below.

Table 16: Water Productivity

	WP_{blue} (irrigation) kg/m^3			WP_{green} (precipitation) kg/m^3			WP (overall) kg/m^3		
	2018	2019	2020	2018	2019	2020	2018	2019	2020
Median	4.36	4.02	4.91	6.02	5.55	6.78	10.37	9.57	11.70

6.9 Reducing human and environmental toxicity on commercial wine farms

6.9.1 General findings

Based on this on-farm experiment, we provided the first Life Cycle Assessment (LCA) on different domestic wine grape farming practices, all suitable for commercial production in South Africa. Russo et al. (2021) presented the Life Cycle Impact Assessment for the following categories based on Life Cycle Inventory illustrated in table 3. The impacts were calculated based on UseTox Model (cf. chapter 5.3.1). The authors concluded on a rather low sensitivity of this model with regards to changes in the inputs of herbicides and insecticides. The model results were dominated by the irrigation process, hence the domestic production of coal-based electricity (ibid). While impacts on various environmental and human health categories from coal-based electricity are substantial, these effects arising from the use of agrochemicals was not captured. The LCA result did not capture effects on the local population and the local environment in farmlands. Consequently, given the severe effects on human health and the environment of these substances highlighted in chapter 3.4, it is clear that the UseTox 2.0 model is not the right tool to prepare informed decision making with regards to human and environmental toxicity from agricultural products. In the South African context, this shortcoming is amplified by the fact that manual labour plays a substantial role in vineyards (Russo et al., 2021).

We therefore underscore the need to assess herbicides, insecticides and fungicides apart from the current LCA methodology and based on a toxicity scoring system that provides the best available estimate on the assessment of several human and environmental health categories on the level of the single ingredients. While this was beyond the scope of this trial, we attach suitable material in the Annex. The material was compiled by Lars Neumeister (personal communication, January 10 2022) based on the AVCASA List of Pesticides 2018; EU Regulation 649/2012 (last consolidated version 01.09.2020); the EU Pesticide Database (January 2022) and the PAN International List of highly hazardous pesticides 2021.

Concerning the domestic standard fertilizer recommendation for cover crops (section 5.1.4) we found no change attributable to fertilizer types and doses provided to cover crops. Given the fact that the cover crops do not provide an additional stream of revenue to the wine farm and their nutrient requirements did not lead to a tangible effect for the vines, we argue that cover crops should not be fertilized at all. This avoids additional cost for wine producers and avoids further environmental burdens from viticulture. Rather, we argue that a species-diverse mix of cover crops including legumes and grains should be used. In the absence of yield-promoting effects of fertilizer doses applied to cover crops, we point out that this fertilizer application is in direct contradiction to the principles of sustainability, wasting money for the farmers while putting additional strain on natural ecosystems.

6.9.2 Replacing insecticides with natural enemies

The control of mealybug with natural enemies was very successful. There was no need for additional pest control with chemical substances apart from the release of the predatory insects Anagyrus pseudococci (parasititc wasp for mealybug control) and Cryptolaemus montrouzieri (predator for mealybug control) from the first year of the trial onwards.

Therefore, we conclude that synthetic insecticides used for mealybug control can be replaced fully with a non-toxic alternative within one year and with no additional equipment.

6.9.3 Terrestrial Ecotoxicity

Irrigation inclusive of electricity accounts for an average of ~54%, followed by Diesel Usage (20%), Fertilisers and Agrochemical production (~20%) and Farming Practices (7.8%). Chlorpyrifos accounts for almost the totality of Farming Practices impacts on Terrestrial Ecotoxicity. Russo et al. (2021), p.1383.

6.9.4 Freshwater Ecotoxicity

Irrigation inclusive of electricity accounts for an average of ~54%. The contribution of Farming Practices ranges from a minimum 4.2% in Scenarios 4 and 8 due to the avoidance of Chlorpyriphos and fertilizer to a maximum of 37.4% (Baseline Scenario). Diesel Usage and Fertilisers and Agrochemical production account for a 5.30 and 5.1% of total impacts on average, respectively. Freshwater Ecotoxicity trace to: Chlorpyrifos and Mancozeb account for 92.7% and 6.3% of emissions to soil respectively to the relative ~38% for Farming Practices; Heavy metal emissions – from fertilisers, pesticides and heavy metal content of plant material – which account for the bulk of the relative share to the overall Freshwater Ecotoxicity. Single contributors were as follows: Irrigation inclusive of electricity (Copper 68.2%, Zinc, 25.6%, Nickel 2.3%), Diesel Usage (Zinc 63.3%, Copper 15.2%, Nickel 5.8%) and Fertiliser and Agrochemical production (Zinc 68.5%, Copper ~13.0%, Nickel 4.7% and Chromium VI 1.1%). Russo et al. (2021), p.1383.

6.9.5 Marine Ecotoxicity

Irrigation inclusive of electricity accounts for an average of ~75% of total impacts. The contribution of Farming Practices ranges from a min 0.6% (Scenario 4) to a max of 13.0% (Baseline Scenario); Diesel Usage and Fertilisers and Agrochemical production account for 7.2% and 6.5% of average impacts, respectively. Substances that contribute to Marine Ecotoxicity are mainly Chlorpyrifos and Mancozeb emitted to soil (95.8% and 1.1% respectively)., Zinc emissions to water (3.0%), arising mainly from Irrigation inclusive of electricity with a ~29% contribution to its relative share and to Diesel Usage with a ~65% contribution to its relative share. Russo et al. (2021), p.1383.

6.9.6 Human Carcinogenic Toxicity

Irrigation inclusive of electricity accounts for an average of 57.5%. Diesel Usage and Fertilisers and Agrochemical production account for a ~35% and 7.3%. Farming Practices had a negligible (0.04%) impact. Human Carcinogenic Toxicity traces to Chromium VI to water arising from each of the main processes, namely Irrigation inclusive of electricity, Diesel Usage and Fertilisers and Agrochemical production, accounting for 60%, ~33% and ~7%, respectively. Interestingly, the Baseline Scenario, which has the highest input of Glyphosate as per [Table 3], showed very low impacts which can be explained by the fact that the carcinogenic effects from Glyphosate were not yet accounted for by the current version of the background data of the toxicity assessment. Russo et al. (2021), p.1383.

6.9.7 Human Non-Carcinogenic Toxicity

Irrigation inclusive of electricity accounts for ~45% of total impacts. Diesel Usage and Fertilisers and Agrochemical production account for an average of 41.4% and 10.7%, respectively. Farming Practices showed little impact (3.1%) on average. Substances that contribute to Human Non-Carcinogenic Toxicity emissions are mainly Zinc emissions to water (60.6%) and soil (32.5%). Russo et al. (2021), p. 1383.

Figure 14: LCIA Results. Global Warming Potential, Terrestrial Acidification, Freshwater Eutrophication, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Human Carcinogenic Toxicity and Human Non-Carcinogenic Toxicity. Russo et al., 2021.

6.9.8 Human Health Damage Assessment

Irrigation inclusive of electricity accounts for ~51% of total impacts. Farming Practices accounts for ~30%, Diesel Usage and Fertilisers and Agrochemical production account for a ~13% and ~6%, respectively. Substances that contribute to Human Health impacts are mainly given by: water consumption at farm (26.3%); Dinitrogen Monoxide (2.9%) arising from farming activities inclusive of diesel, fertilizer and agrochemical production and usage, and Zinc emissions to soil (2.1%) and to water (3.8%). Russo et al. (2021), p. 1383.

As discussed earlier, the Human Health Damage Assessment resulting from the application of UseTox 2.0 was not sensitive to the reduction of herbicides and insecticides with toxic properties. Therefore, we argue that the LCIA results presented below do not reflect the actual improvements regarding human health.

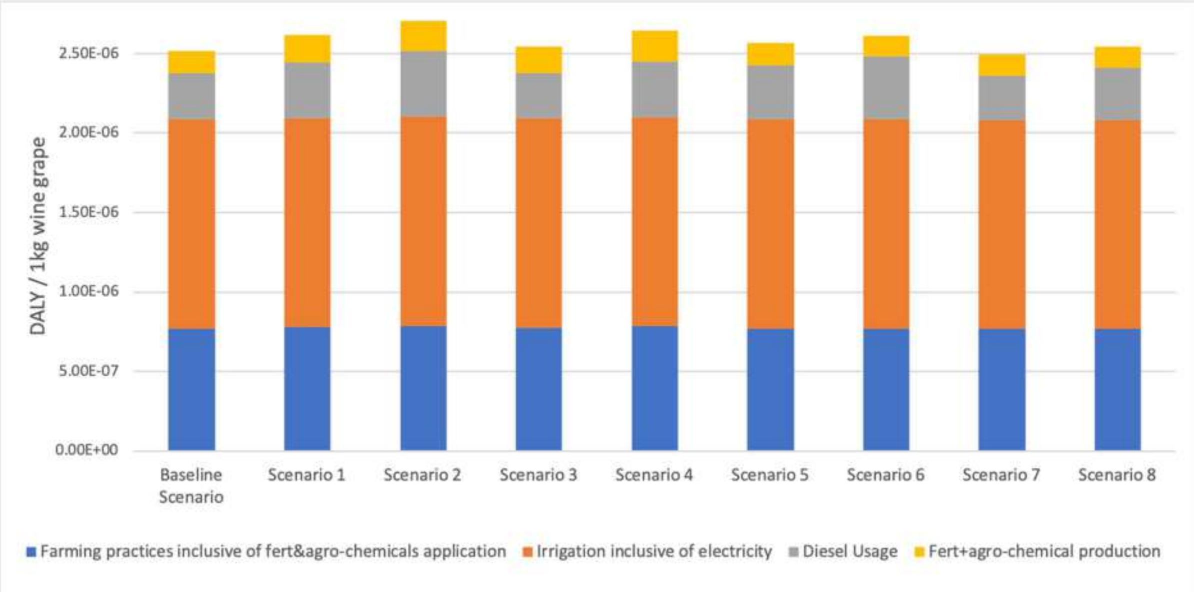


Figure 15:Human Health Damage Assessment Contribution Results. Russo et al., 2021.

6.9.9 Ecosystems Health Damage Assessment

Results across all the scenario are very similar with a spread of 0.14% with Farming Practices accounting for an average of ~95%. Irrigation inclusive of electricity, Diesel Usage and Fertilisers and Agrochemicals production account for a 4.2%, 0.5% and 0.3%, respectively. Main contributors to Ecosystems damage are land occupation (~92%) and water usage (~3%), both related to Farming Practices. Russo et al. (2021), p. 1383.

Again, the Ecosystem Health Damage Assessment resulting from the application of UseTox 2.0 was not sensitive to the reduction of herbicides and insecticides with toxic properties. Therefore, we argue that the LCIA results presented by Russo et al (2021) do not reflect the actual improvements concerning environmental health.

7 Summary and conclusions

The wine industry tells not only a story of tradition but also a story of change. We argue that wine producers are now facing a new and particularly big wave of change, which is driven by rising market forces demanding sustainability, but also by the changing climate. In this report, we aim at contributing to a better understanding of the effectiveness of key elements of sustainable viticulture and how suitable they might be in the context of climate change for domestic vineyards. In the South African context, the already existing gap between water availability from annual rainfalls and water requirements by nature and human activities is expected to broaden further in the upcoming decades. Consequently, sustainability measures must consider an increasing level of water scarcity during summer months.

Winter cover crops were trialled as a key measure for increasing soil health, biodiversity and reducing herbicides in vineyards. We did not observe a decrease in yield but a statistically significant increase in one out of four treatments. Remarkably, we could not detect a clear pattern between early and late termination of cover crops. The significant *increase* in yield was found for cover crops terminated late. One could conclude that the timing of the termination of cover crop does not matter, but we recommend to be careful with generalizing this result into a broadly applicable conclusion. It has to be considered that this result was obtained in an irrigated vineyard, where drip irrigation supplied approximately 50% of the annual water sources (cf. chapter 5.3.2), counteracting potential additional soil water reductions by cover crops. Therefore, we conclude that, as long as irrigation water sources are available, a winter cover crop does not result in decreased yields and is a suitable sustainability measure. These findings should be investigated further and extended to non-irrigated (dryland) vineyards.

Concerning the application of mulch to vineyards, we trialled wood chip mulch that was available from the regional Working for Water Programme. Since the wood chips had no dedicated use path, there were no opportunity cost for other activities and sectors. This is an important element to consider, because mulching material such as straw usually does not exist in abundance. In three out of four cases, we found a statistically significant increase in yield for mulch treatments. When analysing soil moisture levels and soil temperatures, the mulch treatment showed a positive impact on median soil moisture at 15 cm and at 80 cm depth as well as on median soil temperatures measured at 15 cm depth. Based on our data, mulch led to a slower drying and to a slower heating of the soil. We suggest that – given the availability of sustainable sources – the mulching of vineyards should be implemented as a sustainability measure increasing the resilience to climate change impacts.

Given our findings concerning soil parameters, we highly recommend to update current domestic fertilizer recommendations for cover crop. We could not observe a beneficial effect arising from this measure and highlight adverse environmental effects from excess fertilizer application. In brief, a cover crop should not be fertilized. Concerning sustainable fertilizer sources for vines, we recommend to opt for local organic sources for several reasons.

In our Life Cycle Assessment, we assessed a variety of environmental and social impact categories. The following ReCiPe 2016 *Midpoint(H) (*Huijbregts et al., 2016) impact categories were analysed: Global Warming Potential, Terrestrial Acidification, Freshwater Eutrophication, Terrestrial Toxicity, Freshwater Toxicity, Marine Toxicity, Human Carcinogenic toxicity and Human Non-Carcinogenic Toxicity. Furthermore, two Damage Assessment categories, namely Human Health and Ecosystems, from ReCiPe 2016 *Endpoint(H)* (ibid.) were included. The toxicity assessment was based on UseTox 2.0 (Fantke et al., 2017). Further, we performed a Water Footprint Analysis based on the AWARE indicator (Boulay et al., 2018) and Farm Water Productivity indicator (Prochnow et al., 2012).
Concerning the category of Global Warming Potential, we found a carbon Footprint of 0.46 kg CO_2-eq per kg wine grapes, largely attributable to the electricity usage from irrigation. Our sensitivity analysis states that the Carbon Footprint can be reduced to 0.27 kg CO_2-eq in a scenario with low irrigation volumes or with a correspondingly high share of renewable energy; or surge to 0.60 kg CO_2-eq if irrigation volumes were increased given the current electricity mix.

Regarding the Water Footprint Assessment, we first analysed the water quantities and then applied the AWARE (Available WAter REmaining) characterization factor to assess the impacts of the water usage. We found a water usage of 0.646 m^3 per 1 kg of wine grapes, consisting of irrigation water (0.315 m^3/ kg) measured on the farm, upstream ancillary processes not directly at farm level (0.002 m^3/ kg) and green water from precipitation (0.329 m^3/ kg) (Russo et al., 2021). The local AWARE indicator for the Perdeberg area of 61.2 m^3-eq/m^3 was applied to the irrigation water, resulting in 19.38 m^3-eq per kg wine grapes. The interpretation of this result is that the production of one kg wine grapes results in a water deficit of ~19 m^3-eq for human activities and the ecosystem (ibid). Further, we suggest that this indicator might underestimate adverse effects during times of drought. For the Water

Productivity indicator, we found an average value of 10.55 kg grapes per m^3 water, which includes irrigation water (blue water) and precipitation (green water).

Based on our research, the environmental and human toxicity related to the use of pesticides can be reduced substantially. Clearly, the UseTox 2.0 methodology (Fantke et al., 2017) did not provide a base for decision making on this matter and therefore, the method is not suitable to assess the toxicity in LCAs of agricultural products. The annex of this report contains a list of highly hazardous pesticides that should be limited in vineyards and orchards to improve the risks for people living and working in the winelands as well as the natural environment. As an alternative to the use of insecticides, we trialled the control of mealybug with natural enemies with great success. There was no need for additional pest control with chemical substances apart from the release of the predatory insects from the first year of the trial onwards. Therefore, we conclude that synthetic insecticides used for mealybug control can be replaced fully with a non-toxic alternative within one year and with no additional equipment. This is an inspiring example of exchanging pesticides with a high toxicity score for a non-toxic alternative while ensuring crop health.

Based on our findings, we recommend to broadly implement the following elements of sustainable viticulture:

1. Weed control in irrigated vineyards by a species-diverse winter cover crop, thereby reducing herbicide applications;
2. No fertilizer applications to the cover crop;
3. Application of a thick mulch cover in the undervine section;
4. Replacement of synthetic insecticides with 'natural enemies' and pheromones;
5. Limiting the use of herbicides and fungicides to those with a low environmental and human toxicity score, see annex;
6. Modifying the energy supply of irrigation equipment to solar energy and opting for energy-efficient pumping systems.

We suggest to enlarge the time frame of our study to better understand the long-term effects and correlations between the single parameters presented in this report. Further, we recommend to obtain a more detailed understanding of the potential contribution of cover crops to the nutrient supply of vines, their potential to replace synthetic fertilizer and their contribution to an increase in the humus content in domestic vineyards.

8 Literature

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9 Annex: Highly hazardous pesticides authorized in South Africa

The following list of highly hazardous pesticides authorized in South Africa was provided by Lars Neumeister (personal communication, January 10 2022.).

We recommend decision makers to assess alternatives to the substances listed in this annex. From the perspective of social and environmental sustainability, the use of these pesticides must be limited and minimized.

Highly hazardous pesticides authorized in South Africa

				Acute Toxicity			Chronic Toxicity				International Conventions			Environmental Fate and Toxicity			
	Active ingredient	CAS	Group	WHO Ia	WHO Ib	GHS H330	Cancer Classification	Muta (GHS 1)	Repro (GHS 1)	PAN EU EDC	POP	PIC	Montreal	vB	vP W	vP WS	high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
1.	1,3-dichloropropene	542-75-6	1				Probable										
2.	Abamectin	71751-41-2	2			Yes											Yes
3.	Acephate	30560-19-1	1														Yes
4.	Acetochlor	34256-82-1	1							Yes							
5.	Acrinathrin	101007-06-1	1														Yes
6.	Alachlor	15972-60-8	2							Yes		Yes					
7.	Aluminum phosphide	20859-73-8	2			Yes											Yes
8.	Amitrole	61-82-5	1							Yes							
9.	Atrazine	1912-24-9	1							Yes							
10.	Azinphos-methyl	86-50-0	4		Yes	Yes						Yes					Yes
11.	Bendiocarb	22781-23-3	1														Yes
12.	Benfuracarb	82560-54-1	1														Yes
13.	Benomyl	17804-35-2	2					Yes	Yes								
14.	Benthiavalicarb-isopropyl	177406-68-7	1				Probable										
15.	Beta-cyfluthrin; Cyfluthrin	68359-37-5	3		Yes	Yes											Yes
16.	Beta-cyfluthrin; Cyfluthrin	68359-37-5b	2		Yes	Yes											
17.	Bifenthrin	82657-04-3	2							Yes							Yes
18.	Bioresmethrin	28434-01-7	1														Yes
19.	Boric acid	10043-35-3	2						Yes	Yes							
20.	Brodifacoum	56073-10-0	3	Yes		Yes			Yes								
21.	Bromadiolone	28772-56-7	3	Yes		Yes			Yes								

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

	Active ingredient	CAS	Group	Acute Toxicity WHO Ia	Acute Toxicity WHO Ib	Acute Toxicity GHS H330	Chronic Toxicity Cancer Classification	Chronic Toxicity Muta (GHS 1)	Chronic Toxicity Repro (GHS 1)	PAN EU EDC	International Conventions POP	International Conventions PIC	International Conventions Montreal	Environmental Fate and Toxicity vB	Environmental Fate and Toxicity vP W	Environmental Fate and Toxicity vP WS	Environmental Fate and Toxicity high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
22.	Bromethalin	63333-35-7	2	Yes										Yes			
23.	Bromoxynil	1689-84-5	1			Yes											
24.	Bromoxynil octanoate	1689-99-2	1											Yes			
25.	Cadusafos	95465-99-9	3		Yes											Yes	Yes
26.	Carbaryl	63-25-2	3				Probable			Yes							Yes
27.	Carbendazim	10605-21-7	2					Yes	Yes								
28.	Carbofuran	1563-66-2	3		Yes	Yes											Yes
29.	Carbosulfan	55285-14-8	2			Yes											Yes
30.	Chlorantraniliprole	500008-45-7	1													Yes	
31.	Chlorfenapyr	122453-73-0	1														Yes
32.	Chlorfluazuron	71422-67-8	1											Yes			
33.	Chloropicrin	76-06-2	1			Yes											
34.	Chlorothalonil	1897-45-6	2			Yes	Probable										
35.	Chlorpyrifos	2921-88-2	1														Yes
36.	Chlorpyrifos-methyl	5598-13-0	1														Yes
37.	Clothianidin	210880-92-5	1														Yes
38.	Copper hydroxide	20427-59-2	2			Yes										Yes	
39.	Coumatetralyl	5836-29-3	3		Yes	Yes			Yes								
40.	Creosote	8001-58-9	1				Probable										
41.	Cyanamide	420-04-2	1							Yes							
42.	Cyhalothrin	68085-85-8	1														Yes

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

				Acute Toxicity			Chronic Toxicity				International Conventions			Environmental Fate and Toxicity			
	Active ingredient	CAS	Group	WHO Ia	WHO Ib	GHS H330	Cancer Classification	Muta (GHS 1)	Repro (GHS 1)	PAN EU EDC	POP	PIC	Montreal	vB	vP W	vP WS	high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
43.	Cyhalothrin, gamma	76703-62-3	1														Yes
44.	Cyhexatin	13121-70-5	1											Yes			
45.	Cypermethrin	52315-07-8	1														Yes
46.	Cypermethrin, alpha	67375-30-8	1														Yes
47.	Cyproconazole	94361-06-5	1						Yes								
48.	Daminozide	1596-84-5	1				Probable										
49.	DDT	50-29-3	5				Probable			Yes	Yes	Yes				Yes	
50.	Deltamethrin	52918-63-5	2							Yes							Yes
51.	Demeton-S-methyl	919-86-8	2		Yes												Yes
52.	Diafenthiuron	80060-09-9	1														Yes
53.	Diazinon	333-41-5	2				Probable										Yes
54.	Dichlorvos; DDVP	62-73-7	3		Yes	Yes											Yes
55.	Diclofop-methyl	51338-27-3	1				Probable										
56.	Difenacoum	56073-07-5	4	Yes		Yes			Yes					Yes		Yes	
57.	Difethialone	104653-34-1	3	Yes		Yes			Yes								
58.	Dimethoate	60-51-5	1														Yes
59.	Diphacinone	82-66-6	1	Yes													
60.	Diquat dibromide	85-00-7	1			Yes											
61.	Diuron	330-54-1	1				Probable										
62.	Emamectin benzoate	155569-91-8	2													Yes	Yes
63.	Epoxiconazole	133855-98-8	3				Probable		Yes	Yes							

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

	Active ingredient	CAS	Group	Acute Toxicity: WHO Ia	Acute Toxicity: WHO Ib	Acute Toxicity: GHS H330	Chronic Toxicity: Cancer Classification	Chronic Toxicity: Muta (GHS 1)	Chronic Toxicity: Repro (GHS 1)	PAN EU EDC	International Conventions: POP	International Conventions: PIC	International Conventions: Montreal	Environmental Fate and Toxicity: vB	Environmental Fate and Toxicity: vP W	Environmental Fate and Toxicity: vP WS	Environmental Fate and Toxicity: high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
64.	Esfenvalerate	66230-04-4	1														Yes
65.	Ethoprophos; Ethoprop	13194-48-4	3	Yes		Yes	Probable										
66.	Ethylene dibromide; 1,2-	106-93-4	3				Probable			Yes		Yes					
67.	Fenamiphos	22224-92-6	3		Yes	Yes											Yes
68.	Fenarimol	60168-88-9	1							Yes							
69.	Fenazaquin	120928-09-8	1														Yes
70.	Fenbutatin-oxide	13356-08-6	2			Yes										Yes	
71.	Fenitrothion	122-14-5	2							Yes							Yes
72.	Fenpropathrin	39515-41-8	2			Yes											Yes
73.	Fenpyroximate	134098-61-6	1			Yes											
74.	Fenthion	55-38-9	1														Yes
75.	Fentin hydroxide	76-87-9	3			Yes	Probable			Yes							
76.	Fenvalerate	51630-58-1	1														Yes
77.	Fipronil	120068-37-3	1														Yes
78.	Flocoumafen	90035-08-8	3	Yes		Yes			Yes								
79.	Flubendiamide	272451-65-7	1													Yes	
80.	Flufenoxuron	101463-69-8	1											Yes			
81.	Flumetralin	62924-70-3	1											Yes			
82.	Flumioxazin	103361-09-7	1						Yes								
83.	Flusilazole	85509-19-9	1						Yes								
84.	Folpet	133-07-3	1				Probable										

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

	Active ingredient	CAS	Group	Acute Toxicity			Chronic Toxicity				International Conventions			Environmental Fate and Toxicity			
				WHO Ia	WHO Ib	GHS H330	Cancer Classification	Muta (GHS 1)	Repro (GHS 1)	PAN EU EDC	POP	PIC	Montreal	vB	vP W	vP WS	high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
85.	Formetanate	22259-30-9	3		Yes	Yes											Yes
86.	Fosthiazate	98886-44-3	1														Yes
87.	Furilazole	121776-33-8	1				Probable										
88.	Glufosinate-ammonium	77182-82-2	1						Yes								
89.	Glyphosate	1071-83-6	1				Probable										
90.	Imazalil	35554-44-0	1				Probable										
91.	Imidacloprid	138261-41-3	1														Yes
92.	Imiprothrin	72963-72-5	1														Yes
93.	Indoxacarb	173584-44-6	1														Yes
94.	Ioxynil	1689-83-4	1							Yes							
95.	Iprodione	36734-19-7	1				Probable										
96.	Iprovalicarb	140923-17-7	1				Probable										
97.	Isoxaflutole	141112-29-0	1				Probable										
98.	Kresoxim-methyl	143390-89-0	1				Probable										
99.	Lambda-cyhalothrin	91465-08-6	3			Yes				Yes							Yes
100.	Linuron	330-55-2	2						Yes	Yes							
101.	Lufenuron	103055-07-8	1											Yes	Yes	Yes	
102.	Magnesium phosphide	12057-74-8	1			Yes											
103.	Malathion	121-75-5	2				Probable										Yes
104.	Mancozeb	8018-01-7	2				Probable			Yes							
105.	Maneb	12427-38-2	2				Probable			Yes							

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide

Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

				Acute Toxicity			Chronic Toxicity				International Conventions			Environmental Fate and Toxicity			
	Active ingredient	CAS	Group	WHO Ia	WHO Ib	GHS H330	Cancer Classification	Muta (GHS 1)	Repro (GHS 1)	PAN EU EDC	POP	PIC	Montreal	vB	vP W	vP WS	high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
106.	Metam-potassium	137-41-7	1				Probable										
107.	Metam-sodium	137-42-8	2				Probable			Yes							
108.	Methamidophos	10265-92-6	3		Yes	Yes											Yes
109.	Methidathion	950-37-8	2		Yes												Yes
110.	Methiocarb	2032-65-7	2		Yes												Yes
111.	Methomyl	16752-77-5	2		Yes												Yes
112.	Methyl bromide	74-83-9	1										Yes				
113.	Metiram	9006-42-2	2				Probable			Yes							
114.	Metribuzin	21087-64-9	1							Yes							
115.	Mevinphos	7786-34-7	2	Yes													Yes
116.	Milbemectin	51596-10-2s	0														
117.	Naled	300-76-5	1														Yes
118.	Omethoate	1113-02-6	3		Yes					Yes							Yes
119.	Oryzalin	19044-88-3	1				Probable										
120.	Oxadiazon	19666-30-9	1				Probable										
121.	Oxamyl	23135-22-0	3		Yes	Yes											Yes
122.	Oxyfluorfen	42874-03-3	1				Probable										
123.	Paraquat dichloride	1910-42-5	1			Yes											
124.	Parathion	56-38-2	4	Yes		Yes						Yes					Yes
125.	Parathion-methyl	298-00-0	2	Yes		Yes											
126.	PCP; Pentachlorphenol	87-86-5	6		Yes	Yes	Probable			Yes	Yes	Yes					

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

	Active ingredient	CAS	Group	Acute Toxicity WHO Ia	Acute Toxicity WHO Ib	GHS H330	Chronic Toxicity Cancer Classification	Muta (GHS 1)	Repro (GHS 1)	PAN EU EDC	International Conventions POP	PIC	Montreal	Environmental Fate and Toxicity vB	vP W	vP WS	high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
127.	Pendimethalin	40487-42-1	**1**											Yes		Yes	
128.	Permethrin	52645-53-1	**2**				Probable										Yes
129.	Phenthoate	2597-03-7	**1**														Yes
130.	Picloram	1918-02-1	**1**							Yes							
131.	Pirimicarb	23103-98-2	**2**				Probable									Yes	
132.	Pirimiphos-methyl	29232-93-7	**1**														Yes
133.	Prallethrin	23031-36-9	**1**														Yes
134.	Procymidone	32809-16-8	**2**				Probable			Yes							
135.	Profenofos	41198-08-7	**1**														Yes
136.	Propargite	2312-35-8	**2**				Probable							Yes			
137.	Propiconazole	60207-90-1	**1**						Yes								
138.	Propineb	12071-83-9	**1**				Probable										
139.	Propoxur	114-26-1	**2**				Probable										Yes
140.	Prothiofos	34643-46-4	**1**											Yes			
141.	Pymetrozine	123312-89-0	**1**				Probable										
142.	Pyraflufen-ethyl	129630-19-9	**1**				Probable										
143.	Quinalphos	13593-03-8	**2**							Yes							Yes
144.	Quinolin-8-ol; 8-	148-24-3	**1**						Yes								
145.	Quinoxyfen	124495-18-7	**1**											Yes			
146.	Quizalofop-p-tefuryl	119738-06-6	**1**							Yes							
147.	Spinetoram	187166-15-0	**1**														Yes

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

				Acute Toxicity			Chronic Toxicity				International Conventions			Environmental Fate and Toxicity			
	Active ingredient	CAS	Group	WHO Ia	WHO Ib	GHS H330	Cancer Classification	Muta (GHS 1)	Repro (GHS 1)	PAN EU EDC	POP	PIC	Montreal	vB	vP W	vP WS	high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
148.	Spinosad	168316-95-8	1														Yes
149.	Spirodiclofen	148477-71-8	1				Probable										
150.	Sulfoxaflor	946578-00-3	1														Yes
151.	TCMTB	21564-17-0	1			Yes											
152.	Tefluthrin	79538-32-2	3		Yes	Yes											Yes
153.	Temephos	3383-96-8	1														Yes
154.	Tepraloxydim	149979-41-9	1							Yes							
155.	Terbufos	13071-79-9	1	Yes													
156.	Terbutryn	886-50-0	1							Yes							
157.	Tetrachlorvinphos	22248-79-9	2				Probable										Yes
158.	Tetraconazole	112281-77-3	1				Probable										
159.	Tetramethrin	7696-12-0	1														Yes
160.	Thiacloprid	111988-49-9	2				Probable		Yes								
161.	Thiamethoxam	153719-23-4	1														Yes
162.	Thiodicarb	59669-26-0	2				Probable										Yes
163.	Thiophanate-methyl	23564-05-8	1				Probable										
164.	Thiram	137-26-8	1							Yes							
165.	Tri-allate	2303-17-5	1													Yes	
166.	Triadimenol	55219-65-3	1						Yes								
167.	Trichlorfon	52-68-6	3							Yes		Yes					Yes
168.	Tridemorph	81412-43-3	1						Yes								

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)

Highly hazardous pesticides authorized in South Africa

	Active ingredient	CAS	Group	Acute Toxicity: WHO Ia	Acute Toxicity: WHO Ib	Acute Toxicity: GHS H330	Chronic Toxicity: Cancer Classification	Chronic Toxicity: Muta (GHS 1)	Chronic Toxicity: Repro (GHS 1)	PAN EU EDC	International Conventions: POP	International Conventions: PIC	International Conventions: Montreal	Environmental Fate and Toxicity: vB	Environmental Fate and Toxicity: vP W	Environmental Fate and Toxicity: vP WS	Environmental Fate and Toxicity: high bee tox
			∑	12	20	36	46	2	20	35	2	7	1	13	19	13	71
169.	Trifluralin	1582-09-8	2							Yes				Yes		Yes	
170.	zeta-Cypermethrin	52315-07-8z	2		Yes												Yes
171.	Zinc phosphide	1314-84-7	1		Yes												
172.	Zineb	12122-67-7	1							Yes							

Arsenic Pesticides: MSMA. calcium arsenate, arsenic pentoxide
Mineral oils qualify as HHP (carcinogenicity) when cont. > 3% DMSO (see GHS)