Quantification of Soil Carbon Sequestration Potential in Dryland Micro-Rainwater Harvesting Structures

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ICARDA
Science for resilient livelihoods in dry areas

Quantification of Soil Carbon Sequestration Potential in Dryland Micro-Rainwater Harvesting Structures

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Preface

This thesis is presented in partial fulfilment of the requirements of the Utrecht University MSc Earth Sciences programme, study track Earth Surface and Water. The project that this thesis reports on is very different from the one originally proposed more than a year ago. As the Covid-19 pandemic has changed so much of the world, this thesis changed from a primarily field-based project in Jordan to one based much more upon modelling at home.

I am deeply grateful to a number of people for their support in completing the project. Firstly, to Geert Sterk for his overall supervision and direction, constructive criticism and reviewing of results and drafts of this report. Secondly, to Jorge Alvaro-Fuentes of the Spanish National Research Council for his support with using the RothC model and assistance in trouble shooting problems as they arose. Finally, to Mira Haddad and Stefan Strohmeier from ICARDA for more encouragement and assistance than could ever have been asked, even from two time zones away. In particular, their insights on local ground conditions and field data were invaluable to the successful completion of this project, and I am most grateful for those.

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Abstract

Arid regions cover around one third of the Earth's land surface, including 80% of Jordan. These regions may be suitable for the storage of carbon in their soils, providing environmental and economic benefits. This study was conducted to quantify the potential for soil carbon sequestration in dryland micro-rainwater harvesting (Vallerani) structures. The effect of changing climatic and land management conditions was investigated at the International Centre for Agricultural Research (ICARDA) field site in Al Majidiyya, Jordan. Field data was combined with modelling of carbon stocks using RothC-26.3 to meet this aim. Upscaling of the results and consideration of resultant ecosystem services was completed using the inVEST modelling tools. Results suggest that implementing Vallerani structures can lead to an increase in carbon stocks of 1.75 t/ha at the structure ridge and 4.26 t/ha in the structure furrow over a ten-year period. Upscaling these results shows a sequestration potential of 7.9 ± 0.76 t C at the study site, and almost 3 million tons across the Badia as a whole. Ecosystem service modelling demonstrates a potential economic cost of this sequestration to Jordan of as little as $17/ha, covering a large proportion of the implementation costs, even before benefits from increased food production, habitat improvement and other ecosystem services are considered. These results demonstrate that dryland water harvesting offers the potential for significant carbon sequestration compared to natural conditions. Further work should focus on constraining the economic costs and benefits to further expanding the water harvesting structures, as well as the impact of climate change on these predictions.

***Key Words**: Drylands, Soil Carbon Sequestration, Water Harvesting, Ecosystem Services*

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1: Introduction

1.1: Background

Arid regions are areas where there exists a large deficit between the amount of precipitation received and the amount of water lost to evapotranspiration (Nicholson, 2011). These areas cover approximately one third of the Earth's surface, and are, by their nature, vulnerable to fluctuating and low water availability, difficulties in sufficient food production and high amounts of land degradation (Stringer et al., 2012). The site of this research, the Jordanian Badia, is one such arid region.

The Badia is a desert landscape covering more than 80% of Jordan and home to 6.5% and 75% of the country's human and livestock population respectively (Oweis and Hachum, 2006). The region is an important one for agriculture, with the primary land uses being the production of barley and rangeland (Al-Bakri et al., 2001). For this reason, good soil health is of vital importance to the success of the area, but in reality soil quality is often poor, with low infiltration potential and significant surface crusting (Karrou et al., 2011). One potential way of improving the health of soil is through soil carbon sequestration-the process by which atmospheric carbon dioxide (CO_2) is fixed into soil organic matter (SOM). This process is primarily driven by plant photosynthesis and has a number of benefits at both the local and international scale. Locally, increased soil carbon sequestration results in healthier soil, which in turn can lead to increased agricultural yields. At a larger scale, soil carbon sequestration represents a promising, albeit underutilised, method of reducing the amount of CO_2 present in the modern atmosphere (McCarl and Schneider, 2001; Amundson and Biardeau, 2018).

It is proposed that Vallerani micro-scale water harvesting structures may be able to increase these rates of carbon sequestration in arid regions leading to the benefits, or ecosystem services, outlined above. These structures are able to capture the limited precipitation and resultant runoff that occurs and give it time to infiltrate far deeper into the soil than is usually possible with the crusted soil present. The structures are far quicker to install than traditional water harvesting structures, with the potential for 10 to 14 hectares of land to be prepared per day, each containing around 500 micro-catchments, with the use of a single heavy-duty tractor (Berrahmouni et al., 2017). As such, they offer a promising method of harvesting water and increasing agricultural yields, which are capable of being implemented in the local environment.

1.2: Problem Definition

Degraded soils are an issue worldwide, especially in dryland, or arid, regions (Dregne, 2002; Zika and Erb, 2009). It is well established that the health of soil can be improved by increasing its soil organic component and that this can be achieved, at least in part, through soil carbon sequestration (Jastrow et al., 2007). In arid regions, it is also imperative to increase the amount of water that is stored if agriculture is to be possible, as water supply frequently represents the limiting factor on agricultural production in these areas (Elliot et al., 2014). Ensuring agricultural productivity in the area is of major concern for policymakers and the scientific community because as population continues to grow, so too do concerns about the feasibility of feeding this population. (Doocy et al., 2011; Al-Bakri et al., 2013).

Additionally, the inhabitants of the Badia (Bedouins), have traditionally relied on following rainfall patterns in order to graze their livestock. If soil degradation continues unchecked, then there is a risk of sufficient quality pasture being unavailable, and irreparable damage occurring to a nomadic way of life that has persisted in Jordan since at least the 14th century (Bille, 2012). It is anticipated that these issues are likely to be exasperated in the future by the changing climate, with both increasing temperatures and decreasing precipitation expected in the region over the next 80 years (Van Vuuren et al., 2011).

In many developing regions, including the Jordanian Badia, the use of Vallerani water harvesting structures has been shown to be an effective method of increasing soil water content and agricultural yields (Malagnoux, 2008). Several studies (e.g. Faloon et al., 2007; Cornelis et al., 2013) have proposed that these structures can also have the additional benefit of promoting soil carbon sequestration, but to date, this potential has yet to be quantified. This project will seek to address this gap in knowledge, through the use of a combined field and modelling study. Modelling is a necessary component of this study because soil organic carbon levels can take around 10 years to change significantly in dryland areas (Smith, 2004), and International Centre for Agricultural Research in the Dry Areas (ICARDA) projects are generally pilots to test the scientific feasibility of an idea or intervention, running for just 3 to 5 years (Adeel, 2003), meaning that repeated field sampling over time is not possible.

The costs of any intervention to people and environment are always an important consideration, but especially so when the proposed work is focused in a developing region, where vulnerability to a changing climate and other external shocks is generally higher (Yadav and Lal, 2018). It is for this reason that a focus on ecosystem services is also an important part of this study.

1.3: Aims and Objectives

This project uses the RothC-26.3 carbon turnover and inVEST ecosystem services model, combined with data collected from an International Centre for Agricultural Research in the Dry Areas (ICARDA) field site in the Jordanian Badia, in order to meet the stated project aim of quantifying the carbon sequestration potential and feasibility of Vallerani systems in the Jordanian Badia. Achieving this aim involved the completion of the following objectives;

1) Quantifying the potential carbon sequestration of a single Vallerani system
2) Upscaling these results to assess how much carbon can be sequestered in larger scale water harvesting schemes, at both the whole catchment (km) and whole landscape/ Badia (100's km) scale
3) Assessing the costs and benefits (ecosystem services) associated with the implementation of these systems at the whole Badia scale

2: Background

2.1: Arid Regions

Precise definitions of an arid region vary by source, but an overarching theme is a large imbalance between the amount of precipitation an area receives, and the amount of water that is lost through evapotranspiration. The commonly used approach of the Food and Agricultural Organization of the United Nations (FAO) defines an arid region as an area where the ratio of precipitation to potential evapotranspiration, or the climatic aridity index, is less than 0.50. Using this definition, it is also possible to separate the general term of 'arid region' into three categories (Salem, 1989; Nicholson, 2011);

1) Hyper-arid zone, where the aridity index is less than 0.03 and vegetation cover is limited to scattered shrubs. In these areas, precipitation is extremely irregular, with the potential for multiple years of no precipitation, and annual precipitation rarely exceeding 100mm. As such, hyper-arid regions are unsuitable for agriculture.
2) Arid zone, where the aridity index is between 0.03 and 0.20. Whilst native (or naturally occurring) vegetation is sparse, agriculture is possible with irrigation. Precipitation is highly variable, at between 100 and 300mm per year.
3) Semi-arid zone, where the aridity index is between 0.20 and 0.50. Rain fed agriculture can be supported to a limited extent, and there is some natural vegetation cover, although this is mostly limited to grass like plants and shrubs. Annual precipitation can vary greatly but is usually less than 800mm.

Using these definitions, around one third of the Earth's land area can be considered as arid land, with 4.5%, 15% and 12% land cover respectively for hyper-arid, arid and semi-arid land. Additionally, a further 8 to 10% of Earth's land cover can be designated as 'dry sub humid' where the aridity index is between 0.5 and 0.65 and may be considered drylands under some classifications. As can be seen in *figure 2.1.1* below, these regions are spread across all continents, with the largest arid area extending across northern Africa and through the Middle East into west Asia (WANA regions). The Jordanian Badia (see *3: Study Area*) is one such region.

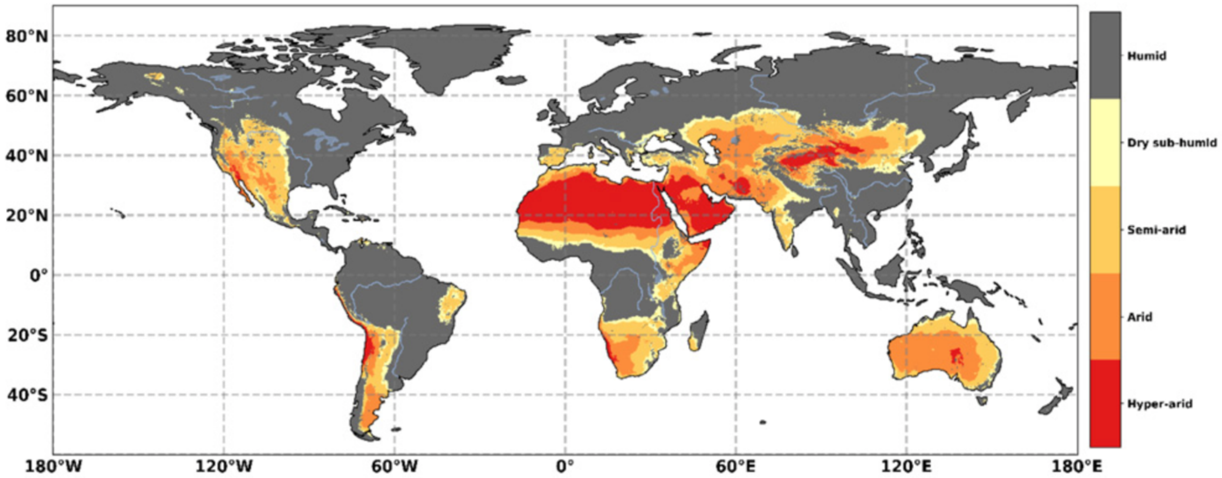


Figure 2.1.1: Global dryland distribution based on aridity index. Adapted from Feng and Fu (2013)

Arid regions present a number of interrelated challenges to those who live there, primarily in terms of water availability, the ability to produce sufficient food, land degradation and the delicate nature of native ecosystems.

Firstly, the world average annual renewable water supply is around 7000 cubic meters per capita, but in WANA regions this falls to an average of just 1500 cubic meters per capita, which is expected to further reduce to less than 700 cubic meters per capita by 2025. Jordan is in a particularly precarious position, with a per capita availability of less than 230 cubic meters (El Kharraz et al., 2012). The average water usage per capita (or 'water footprint') worldwide amounts to around 2480m^3, underscoring the intensity of the water scarcity that Jordanian people face (Hoekstra and Chapagain, 2006).

The effects of water scarcity are also shown in the reduced diversity and productivity of an area's agriculture. The water requirements of different crop species vary greatly from some species of millet requiring around 300mm in a growing period, to sugarcane, which requires up to 2500mm across its growing period. (Smith et al., 1998). Naturally, this means that drylands are unsuitable for many types of agriculture.

Desertification is defined as land degradation in the drylands (Helldén, 1991) such as the Jordanian Badia. It is characterised by a loss of biological productivity and is broadly caused by a loss of soil nutrients (Veron et al., 2006). To some extent, desertification is a natural process in dry regions, because the very limited amount of rainfall and presence of powerful feedbacks means that a single large fire can cause desertification to occur for many subsequent years (Schlesinger et al., 1990). Although some consider the reality or scale of desertification to be less severe than is often stated (Sterk and Stoorvogel, 2020), there is a general consensus that human factors have exacerbated this natural desertification in Jordan. For example, resource mismanagement in the country is endemic, primarily due to a lack of governmental oversight of land ownership, clashes between traditional, nomadic lifestyles and more modern, settled agricultural practices (Al Naber and Molle, 2016; Caulfield et al., 2020) and removal of vegetation for fuel (Oweis and Hachum, 2006).

Furthermore, Jordan experiences an average population growth of more than 2% a year, primarily due to the almost continual political turmoil in neighbouring countries. The resulting refugee crisis has resulted in 3million of Jordan's 9.5million inhabitants holding no legal Jordanian citizenship (Ghazal, 2016), and further intensifies issues of resource allocation. Population growth drives an increased need for food, and economic growth is known to lead to an increased demand for meat and other animal products which require more agricultural land to produce (Marques et al., 2018). Together, these factors have resulted in animal grazing exceeding the available productivity of the grazing resources in the country for many years (Shawehneh et al., 2011), and the United Nations designating land degradation in Jordan as severe since the early 1990's (Khresat et al., 1998).

2.2: Soil Carbon Sequestration

Soil organic matter (SOM) is a key component of healthy soil, which affects the physical, chemical and biological functioning of the land, and affects humans in the form of increased agricultural yields and improved water quality (Ontl and Schulte, 2012). It is primarily formed of bacteria and fungi found in the soil, along with decaying plant and animal material. The amount of soil organic matter that is present is the key control on the soil organic carbon (SOC) levels of that soil. The levels of SOC in the soil are also dependant on the balance of the fluxes between the different elements of the carbon cycle, the relevant portion of which (soil carbon sequestration) is shown below in *figure 2.2.1.*

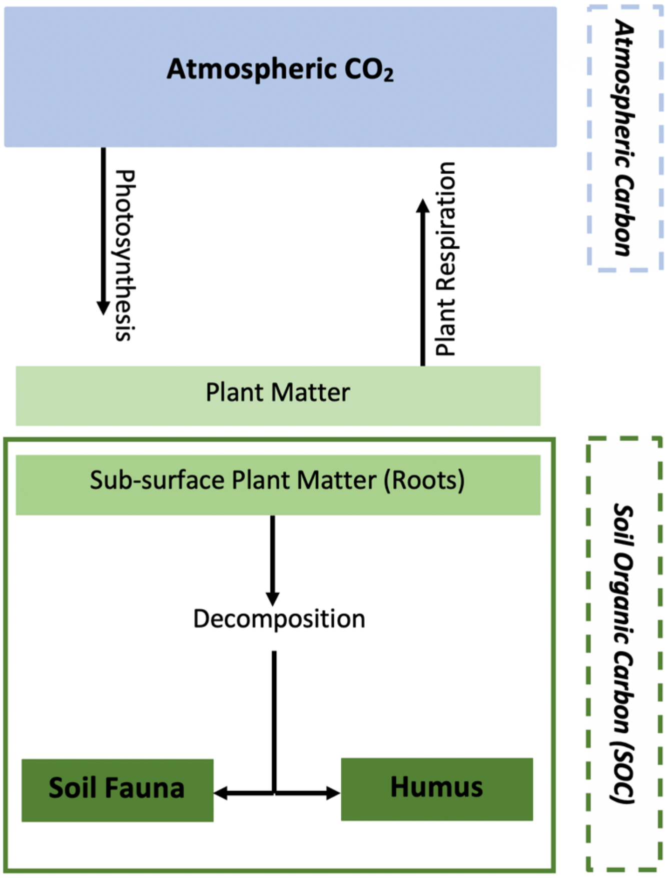


Figure 2.2.1: A section of the carbon cycle, showing the movement of carbon between the atmosphere and soil.

Soil carbon sequestration is a part of this carbon cycle and is primarily a process by which atmospheric CO_2 is converted, or fixated, into soil organic carbon. The most efficient way for this conversion to take place is through plant photosynthesis, and as such, the growth of vegetation is the most commonly utilised method of increasing soil carbon sequestration rates (Lal, 2008). Conversely, historic desertification and loss of vegetation is responsible for an estimated soil carbon loss of between 20 and 30Pg (Lal, 2004).

The potential of soil to store CO_2 is well documented, but actual amounts able to be sequestered varies greatly by soil and land use type (Sleutel et al., 2003; Wiesmeier et al., 2014; Kelland et al., 2020). To date, work that includes Jordan or other similar dryland areas in these projections has been conducted at either the regional (Al-Adamat et al., 2007; Falloon et al., 2007), or global scale (Lal, 2004), and no smaller scale estimation yet exists. Studies specifically considering the potential of water harvesting structures to improve the sequestration of carbon acknowledges the likely important role that such interventions play, but do not yet quantify the potential carbon storage of these systems at a useful scale (Lal et al., 1999; Lal 2004).

2.3: Vallerani Systems

Vallerani systems are named for their creator, Venanzio Vallerani, who began work on their development in Niger in 1988.The website maintained by the Vallerani family considers the storage of CO_2 to be one of the key benefits of implementation, alongside pasture improvement, landscape and groundwater restoration and improved food security (Vallerani System, 2013). A profile and aerial view of a typical system can be seen in *figures 2.3.1* and *2.3.2* respectively. These systems have been shown to be effective in 13 further countries over the last 32 years; Burkina Faso, Chad, China, Egypt, Jordan, Kenya, Morocco, Senegal, Syria, Sudan, Tunisia, Mongolia and Madagascar (Malagnoux, 2008), with shrub survival increasing from 16 to 100% in some areas (Ali and Yazar, 2007).

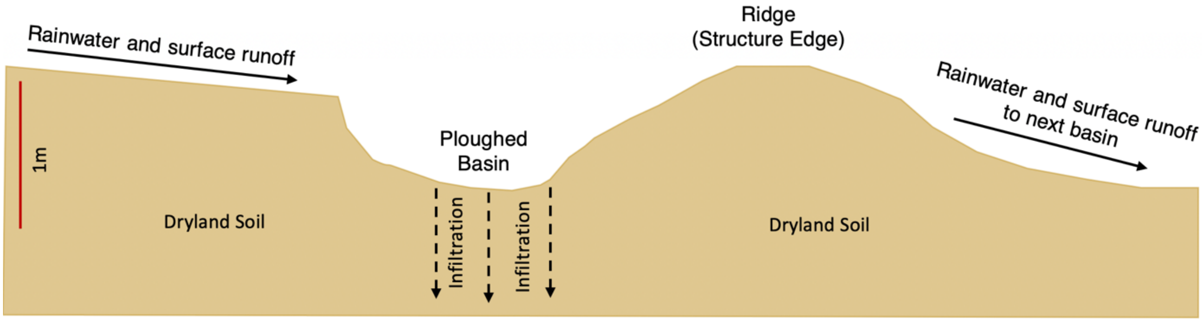


Figure 2.3.1: A profile view of a typical Vallerani system.

Figure 2.3.2: An aerial view of a freshly ploughed field in Oudalan, Burkina Faso, showing multiple Vallerani systems (Taken from Vallerani System, 2013).

The small-scale basins that these systems form are able to capture the limited precipitation and resultant runoff in the area, and allow this water to infiltrate deep into the soil. In this way, a micro-scale rainwater harvesting system is formed, leaving water available for seedling development over long enough timescales to allow vegetation to develop. Vallerani systems are contrasted with macro scale systems which operate across an entire catchment or watershed and are generally more expensive to install and maintain (Critchley et al., 2013). Furthermore, the use of a heavy duty (100+ horsepower) tractor and modified plough means that 10 to 14 hectares of land can be prepared per day, each containing around 500 micro-catchments, making the system far quicker than traditional water harvesting techniques (Berrahmouni et al., 2017). As such, Vallerani systems are the dominant method of water harvesting in WANA regions.

The stated benefits of Vallerani systems (i.e. landscape and groundwater restoration) can be considered as examples of ecosystem restoration, where ecosystem restoration is defined as an attempt to return an ecosystem to an approximation of its original conditions (Mitsch and Jørgensen, 2003; James et al., 2013). In the case of the Badia, a return to original conditions primarily comprises of reversing desertification and increasing vegetation cover (Oweis, 2017).

3: Study Area

3.1: Location and Background

Jordan, or more formally, the Hashemite Kingdom of Jordan, is a Middle Eastern country to the south-east of the Mediterranean Sea. As seen in *figure 3.1.1*, the country is almost entirely landlocked by Saudi Arabia to the south and east, Syria to the north, Iraq to the north-east and Israel and Palestine to the west, with just a 26km coastline with the Red Sea in the extreme south-west of the country.

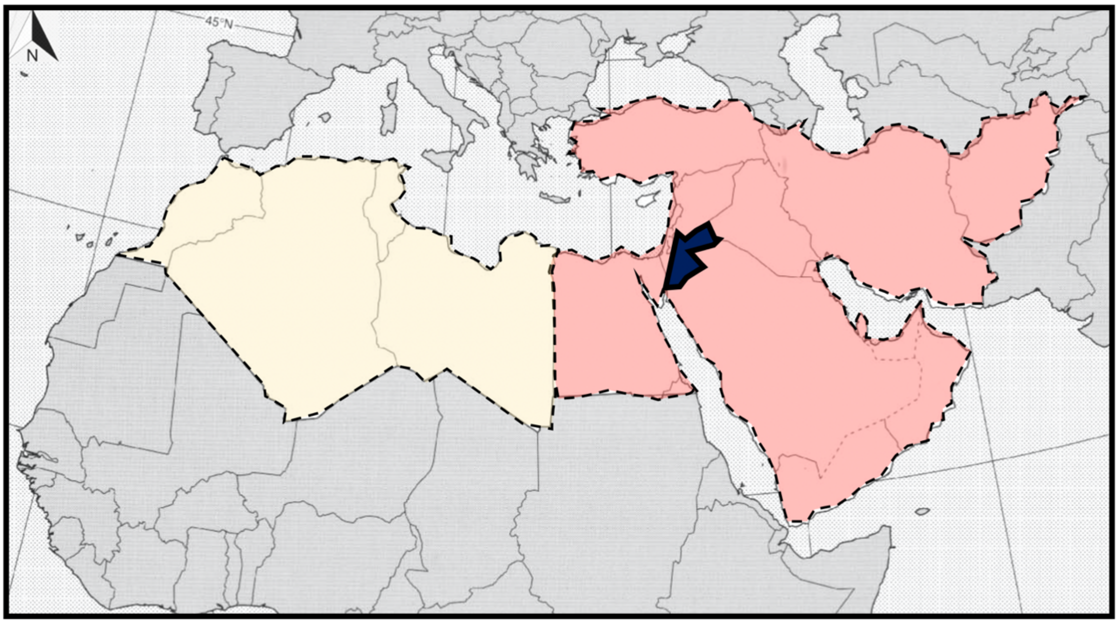


Figure 3.1.1: The Middle East (red) and north Africa (gold) as defined by Zeidan (2020). Jordan is highlighted blue. Base map is open source.

A desert landscape, known locally as the Badia and more formally as the Syrian Desert, comprises a little over 80% of the country (Karrou et al., 2011). The region is named for the Bedouin people who historically inhabit the area, and can be divided into three zones, as shown in *figure 3.1.2:* North, Middle and South.

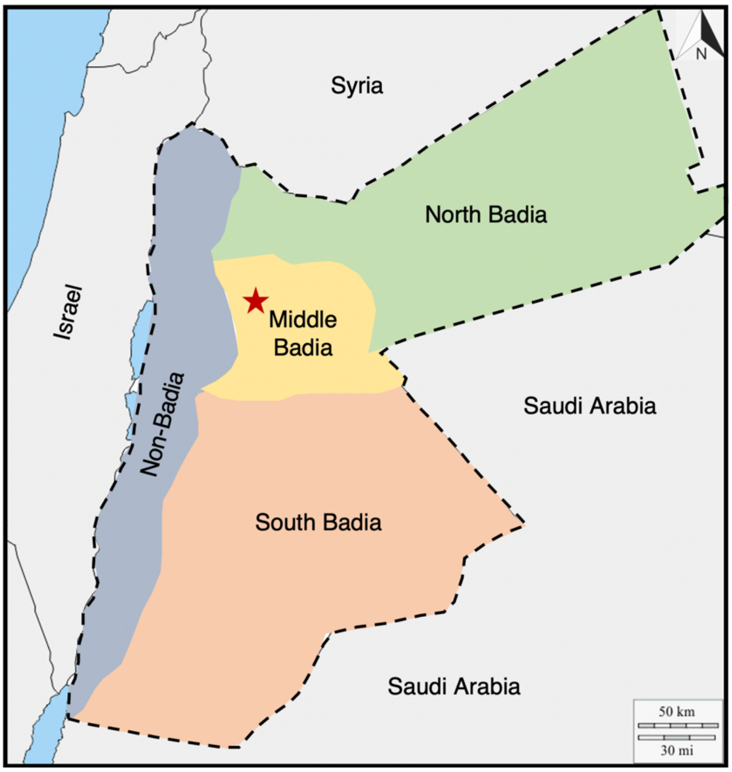


Figure 3.1.2: Division of the Badia, with field site location marked with a star. Base map is open source.

The extreme west of the country is home to the majority (~93%) of its inhabitants, primarily in the capital city, Amman, and the high-density urban areas of Irbid to the north-west (Jordanian Department of Statistics, 2015). The Badia, in contrast, is home to just 6.5% of the human population, but more than 75% of the country's livestock (Oweis and Hachum, 2006). It is an important agricultural region, with the primary land uses being the production of barley and rangeland.

The field site for this study is situated in the middle Badia, around 30km to the south-east of Amman, at Al Majidiyya. This field site was chosen by ICARDA as their Badia benchmark site after a three-stage process where 226 Badia sites were assessed for their suitability based on climate, soil type, watershed area, topography and community presence (Karrou et al., 2011).

3.2: Site Characteristics

The climate of the site can be considered semi-arid to arid, with an annual rainfall average of 152mm. This precipitation is irregular and non-uniform, with the vast majority falling in intense storms between December and March. Daily minimum temperature at the site has averaged to 8.5°C and maximum to 24.5°C (Taimeh, 2003). The aridity of the area is enhanced by highland shield effects to the east and west, and a prevailing dry wind from the west (Tarawneh and Kadıoğlu, 2003). Elevation of the site itself ranges between 650 and 800m with mainly gentle slopes (Mazahreh et al., 2018).

Badia soils are characterised by high silt and calcium carbonate content and depths of 30 to 100cm, with the potential for significant surface crusting and a low soil organic matter content (Karrou et al., 2011). This content, coupled with the sparse vegetation cover, leads to generally low water infiltration rates, in the range of 4-20 mm/hr, and high runoff rates after precipitation (Abu-Awwad et al., 2017). The soil is highly erodible, as demonstrated by the presence of gullies.

4: Materials and Methods

4.1: Overview of Approach

The study focused on the potential for soil carbon sequestration at three different spatial scales; a single Vallerani system (plot scale), a site of multiple systems (catchment scale) and across the whole Badia (landscape scale). At the plot scale, field data from the ICARDA field site (*3: Study Area*) was used to quantify soil carbon sequestration in and around a single system. At the catchment scale, the data collected at the field site was then used as input data to run the soil carbon model RothC-26.3, allowing for quantification of expected soil carbon storage if the Vallerani systems were used at a larger scale. The RothC-26.3 model results were again utilised to further upscale results to an estimation of the soil carbon sequestration across the entirety of the Badia. At this largest scale, consideration was also given to the ecosystem services of these carbon storage scenarios and modelled using the integrated valuation of ecosystem services and trade-offs (inVEST) model. Finally, a comparison between the sequestration results of RothC-26.3 and inVEST was completed.

4.2: Field Sampling

Owing to ongoing travel restrictions throughout 2020, it was not possible to travel to Jordan as had been originally planned. For this reason, field sampling of soil characteristics was completed by ICARDA staff based in Amman. Six Vallerani plots were used in the study; two installed 4 years ago (November 2016), 2 installed 1 year ago (November 2019) and 2 control plots without Vallerani plots. In each of the Vallerani plots, each individual furrow was between 4.0 and 4.5m long and ~0.5m wide, with a depth below the natural land surface of 0.2 to 0.3m, and the adjacent ridge height extending a further 0.3 to 0.5m above this. Spacing of approximately 7m was left between the contours of individual furrows, and in each furrow two shrub seedlings (*Atriplex halimus*) were planted by the local community (Strohmeier et al., 2021). Vegetation cover was more significant in the older of the furrows due to the fact that more time had been allowed for growth and development. Data was recorded on the vegetation cover present at each of the sampling sites for later use in carbon modelling. Ultimately, however, this soil was shown to be so significantly spatially heterogenous that comparison between systems of different ages was not possible, and only data from the 'old' structure (4 years after implementation) was used in the modelling.

Meteorological data was also required from the site. In particular average values of monthly rainfall, open pan evaporation and monthly temperature were obtained from previously collected ICARDA data sets and averaged to the data resolution required.

Laboratory testing was utilised to determine the soil clay percentage, which was required for RothC-26.3 modelling, and soil carbon content, which was vitally important to developing an accurate monitoring of the present-day carbon stocks. Both soil clay percentage and soil carbon content were sampled at depths of 5, 15, 25 and 35cm along 3 transects perpendicular to each Vallerani structure, each containing 5 data collection points (centre of structure, 1.5 and 3m to the left and right), as shown in *figure 4.2.1*. This ensured that data was recorded from the furrow, ridge and interspace of each structure. Soil clay percentage was then quantified using a laboratory particle size analysis, whereby soil is fractionated to sequentially remove smaller and smaller fractions from the soil (Bowman and Hukta, 2002).

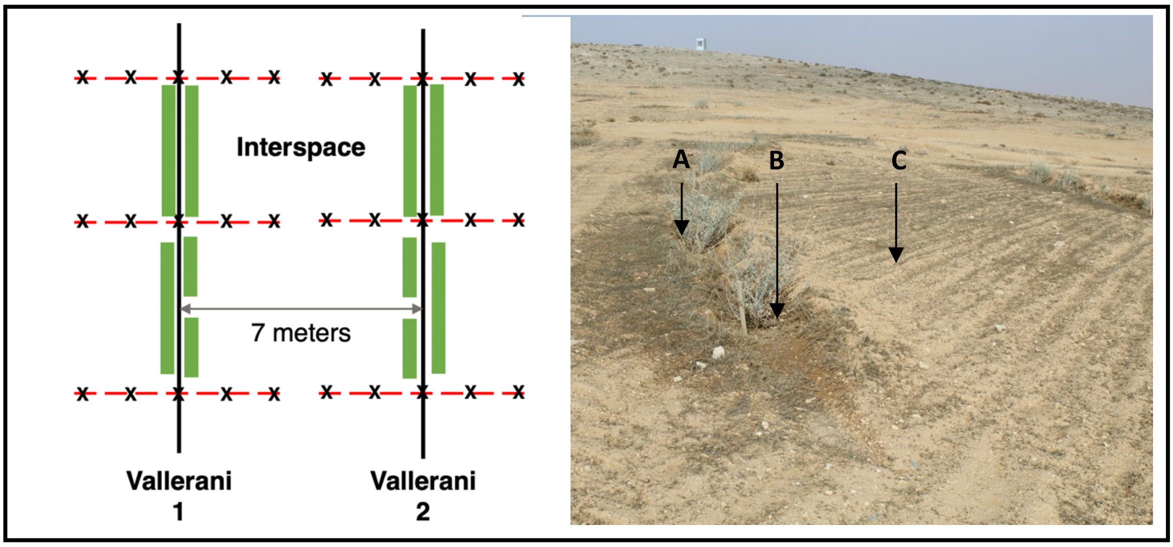


Figure 4.2.1: Sampling structure, where x denotes a core location, black line the furrow and green boxes the Vallerani ridges (left). Image of a single Vallerani structure (right), where A is the furrow, B the ridge and C the interspace.

Soil carbon content was calculated using the standard laboratory procedure of elemental combustion, where a small (< 0.5g) sample of soil is burnt to 900 °C and carbon dioxide output measured. Prior to this, acidification was completed, where hydrochloric acid was used to removed carbonates, so that organic and inorganic carbon could be distinguished from one another (Johns, 2017).

Above ground biomass data was collected using the sampling plot method as described by Ravindranath and Ostwald (2008), whereby 2x2m plots were used to systematically sample vegetation information and drying used to verify the dry weight of the biomass. Below ground biomass is significantly more difficult to measure in situ, especially without damaging the roots of plants. There do exist, however, a number of relationships that can be used to estimate below ground biomass from above ground biomass, with these further explored in *5.1.1: Inputs Calculation*.

Information on the monthly manure input was required for this study. No manure was applied as fertiliser in the study site at any point in the year; however, the impact of grazing male (buck) and female (doe) goats must be considered, especially during the primary grazing season. As Vallerani structures are designed to concentrate runoff into a smaller area, it was probable that goat waste may have also become concentrated after grazing was allowed in the area (2 years after implementation of the Vallerani system). This information was collected by a simple visual estimation- i.e. comparison between photographs, followed by calculation of the input (see *5.1.1: Inputs Calculation*).

4.3: Sequestration Calculation and Uncertainty

Total organic carbon storage was calculated as the total of the carbon contained in above ground biomass, below ground biomass and soil organic carbon. The carbon sequestration in the Vallerani structures was then calculated by finding the difference between the Vallerani plots and the control (interspace) sites, with this difference representing the additional carbon storage that has occurred as a result of the Vallerani intervention.

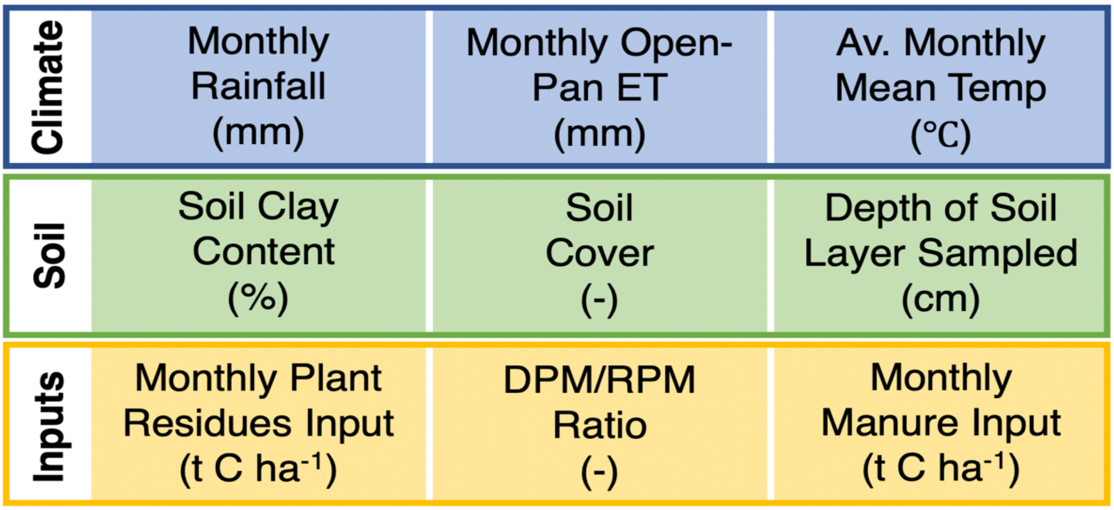
In order to quantify the uncertainty around the data collected, maximum, median and minimum scenarios were defined for each of the data collected for all parameters (e.g. precipitation, above ground biomass). Field data was also considered to have an error margin of ±2.5%, consistent with other, similar, collections of soil data (Vanguelova et al., 2016). This allowed for the calculation of a range of potential sequestration rates, and the confidence in the results to be defined.

4.4: Carbon Modelling

4.4.1: Model Description

RothC-26.3 is a process-based model that simulates the turnover of organic carbon in topsoils, taking account of soil type, temperature, hydrology and plant cover. It is capable of calculating, at monthly time steps, total organic carbon (t ha^{-1}), microbial biomass of carbon (t ha^{-1}) and carbon age (years) over years to centuries timescales (Coleman and Jenkinson, 1996). The model can be run in both forward (where known inputs are used to calculate changes in soil organic matter) and inverse (where inputs are created from known changes in soil organic matter) modes. This study utilises the former mode in order to calculate the amounts of soil organic carbon stored in a Vallerani system.

The data requirements for this model are outlined below in *figure 4.4.1.1.* All of this data was collected during the field sampling described in section *4.2*.



Climate	Monthly Rainfall (mm)	Monthly Open-Pan ET (mm)	Av. Monthly Mean Temp (°C)
Soil	Soil Clay Content (%)	Soil Cover (-)	Depth of Soil Layer Sampled (cm)
Inputs	Monthly Plant Residues Input (t C ha^{-1})	DPM/RPM Ratio (-)	Monthly Manure Input (t C ha^{-1})

Figure 4.4.1.1: RothC-26.3 data requirements according to Coleman and Jenkinson (1996), grouped by data type. DPM is decomposable plant material, and RPM resistant plant material.

These data requirements were determined using an earlier version of the model, itself based on a series of long-term field parametrisation experiments at the Rothamsted research site in Hertfordshire, England. The key justifications for the inclusion of some data is as follows;

1) Air Temperature: Preferred over soil temperature for ease of obtainability at the majority of field sites. In topsoils (i.e. <20 cm depth) temperature is shown to be within +1°C of the annual minimum and -1°C of the annual maximum (Gillabel et al., 2010).
2) Soil Clay Content: Requires laboratory work, so is the most resource intensive data to collect. Essential, however, because it affects organic matter decomposition and plant water availability (Müller and Höper, 2004).
3) Soil Cover: The presence or absence of vegetation must be included as decomposition occurs faster in fallow than cropped soil (Sparling et al., 1982).

4.4.2: Model Structure and Initial Conditions

Initial conditions (i.e. the total initial soil carbon stocks) were estimated from remote sensing data to be around 16 t C/ha (Batjes, 2006; Scharlemann et al., 2014; Hengl et al., 2017). To determine the way in which this initial total carbon stock was partitioned, a sensitivity analysis was conducted. In all scenarios, organic inputs were added at a consistent, and high rate, corresponding to the fastest stage of organic carbon addition expected in a Vallerani furrow. As can be seen in *figure 4.4.2.1*, there was no significant difference in the outputs of the model over a ten-year period when initial soil carbon was divided equally between all five fractions, or increasing any one fraction to 30% of the total initial carbon. The only exception to this is where the percentage of decomposable plant material (DPM) (Se2 and Se5) was increased, where variance figures at each monthly time step were a maximum 5.08% and 9.45% respectively from the average (Se1) conditions.

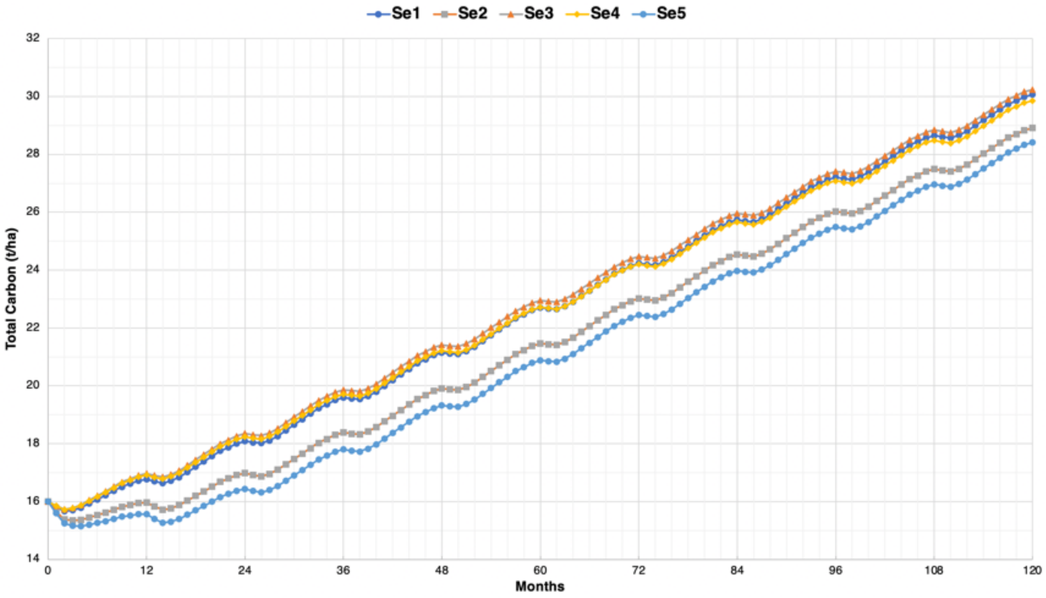


Figure 4.4.2.1: Sensitivity analysis results. See inputs in *table 4.4.2.1* and note that vertical axis does not begin at 0.

Due to the very small variance between Se1, Se3 and Se4 (<4% at all timesteps), and the fact that research considers Se5 in particular to be unlikely in dryland soils (Farina et al., 2013) equal fractions were used as initial conditions, as shown in *Table 4.4.2.1*.

Table 4.4.2.1: Sensitivity analysis inputs, with ultimately utilised baseline conditions for all model scenarios selected in red (Se1).

Carbon Pool	**Carbon Stock (t C/ha)**				
	Se1	***Se2***	***Se3***	***Se4***	***Se5***
Decomposable Plant Material	3.2	4.8	2.8	2.8	5.6
Resistant Plant Material	3.2	2.8	4.8	2.8	1.76
Microbial Biomass	3.2	2.8	2.8	4.8	2.88
Humified Organic Matter	3.2	2.8	2.8	2.8	2.88
Inert Organic Matter	3.2	2.8	2.8	2.8	2.88
Total	*16*	*16*	*16*	*16*	*16*

The organic inputs shown in *figure 4.4.1.1* then enter the model and follow the compartmentalised structure shown below in *figure 4.4.2.2*. All compartments decompose in the same way (although at different proportions). Only one branch is shown below for clarity.

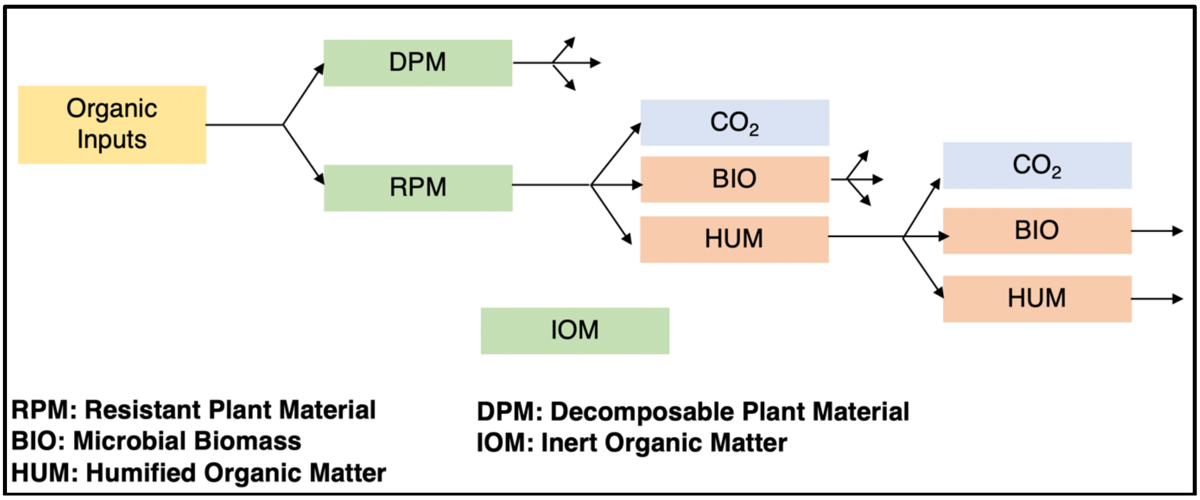


Figure 4.4.2.2: RothC-26.3 model structure, where arrows indicate decay. Inputs are yellow and green, atmospheric outputs blue and outputs that remain in the soil red. Adapted from Coleman and Jenkinson (1996).

The DPM/RPM ratio, controlling subsequent partitioning, is dependent upon the type of incoming plant material and has been determined experimentally for a number of land types. For the site used in this study, the value is 0.67, as the site can be characterised as scrubland or semi desert (Zimmerman et al., 2007).

Decomposition from one compartment (e.g. DPM or RPM) in a given month is defined by *equation 1*;

$$Y\,(1-e^{-abckt}) \tag{1}$$

Where *a*, *b* and *c* are the rate modifying factor for temperature, moisture and soil cover respectively, *k* is the decomposition rate constant for a given compartment and *t* is equal to 1/12 in order to transform *k* from its basis as a yearly decomposition rate to a monthly rate.

Decomposition rate constants are predefined by the Rothamsted experiments and are recommended not to be edited when using the model (Jenkinson et al., 1987; Jenkinson et al., 1992). These factors are given below in *table 4.4.2.2*.

Table 4.4.2.2: Decomposition rate constants for each compartment in RothC-26.3.

Compartment	Decomposition Rate Constant (yr^{-1})
Decomposable Plant Material	10.00
Resistant Plant Material	0.30
Microbial Biomass	0.66
Humified Organic Matter	0.02

Temperature rate modifying factor (*a*) is calculated using *equation 2*;

$$a=\frac{47.91}{1+e^{\left(\frac{106.06}{T+18.27}\right)}} \tag{2}$$

Where T is the average monthly air temperature in degrees centigrade.

Calculation of the moisture rate modifying factor (*b*) requires both the maximum (*equation 3*) and accumulated topsoil moisture deficit (TSMD). Where topsoil is a different thickness than at the Rothamsted test site (23cm) the result of *equation 3* is divided by 23 and multiplied by actual thickness. Where soil is bare for a month, the maximum TSMD is divided by 1.8.

$$Max\;TSMD=-(20.0+1.3(\%clay)-0.01(\%clay)^2) \tag{3}$$

Accumulated TSMD is calculated from the first month where 75% of the open pan evaporation is greater than rainfall and continues until maximum TSMD is reached. Finally, *b* can be defined by *equation 4*;

$$b=1\;for\;accumulated\;TSMD\;<0.444\;maximum\;TSMD \tag{4a}$$

$$b=0.2+(1.0-0.2)*\frac{(max.TSMD-acc.TSMD)}{(max.TSMD-0.444\;max.TSMD)}\;for\;accumulated\;TSMD\;\geq 0.44\;maximum\;TSMD \tag{4b}$$

Soil cover factor (*c*) is assessed on a simple binary basis. Where soil is vegetated, *c*=0.6. Where soil is bare*, c*=1.0. In this study, the threshold for vegetated was set at 35% coverage.

Both DPM and RPM decompose to form BIO and HUM as well as CO_2 in the first stage, with proportions controlled by the clay content of the soil. The ratio of CO_2/(BIO+HUM) is calculated using *equation 5*.

$$x = 1.67\ (1.85 + 1.60 \exp(-0.0786 * \%clay)) \qquad (5)$$

Where x is the ratio of CO_2/(BIO+HUM).

$x/(x+1)$ is then evolved as CO_2 and $1/(x+1)$ forms as BIO + HUM. The BIO + HUM portion is then divided in the proportion 46% BIO and 54% HUM and follows the pathway shown in *figure 4.4.2.3*.

4.4.3: Model Application

Roth C-26.3 was originally designed for arable land in temperate regions, however later versions and improvements of the model (such as the version described above) have been extensively applied to soils in semi-arid environments (Jenkinson et al., 1999; Farage et al., 2007). In this study, the model was initially applied at the scale of a single Vallerani system to test sequestration potential over 10 years compared to baseline scenarios, before upscaling the result to the catchment scale to assess the potential for storage if the Vallerani structures present were implemented across the entire field area.

As the Vallerani does not behave linearly, this study does not add plant inputs in a consistent fashion across the whole study period. As the furrow fills, the rate of increase in plant and litter volume decreases, and therefore so too is the amount of carbon added to the soil (Verbist, 2020). This is simplified in the model so that only 50% the monthly plant input at time step 0 is added in months 25 through to 72 and then 25% in months 73 to 120. This occurs for both the furrow and ridge, however, is unnecessary in the interspace, as plant input is minimal and expected to remain constant across the ten-year period, as it is natural vegetation and not readily impacted by the implementation of the Vallerani structure.

4.5: Ecosystem Services

4.5.1: Rationale and Description

Ecosystem services can be defined as the benefits that humans experience from healthy ecosystems (Goldstein et al., 2012.). They are usually grouped into four service types, as shown in *figure 4.5.1*, where supporting services underpin provisioning (goods), regulating and cultural services (Reid et al., 2005; Seppelt et al., 2011).

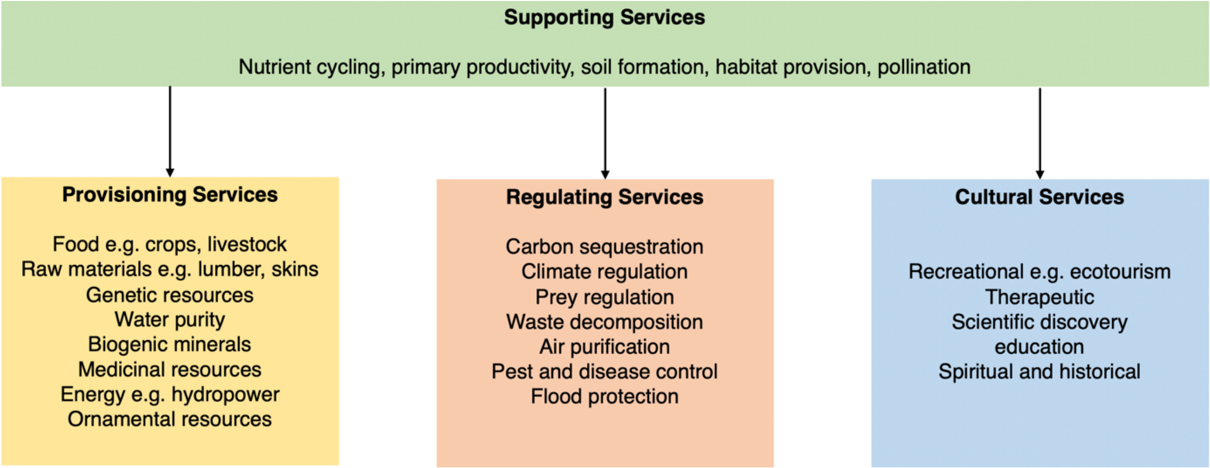


Figure 4.5.1: Structure and examples of ecosystem services. Information from Reid et al., (2005).

Clearly, not all services are relevant to each case. In this study, the focus is on the regulating service of carbon sequestration the provisioning service of food and the supporting services of nutrient cycling and primary productivity. At a larger scale, the Kyoto Protocol and later international climate agreements allows carbon emissions to be offset by demonstrable removal of carbon from the atmosphere; for example, through the improved management of agricultural soils, afforestation and reforestation (Watson et al., 2000; Yokozawa et al., 2010). Successful soil carbon sequestration therefore represents an economic opportunity in developing regions through the implementation of so called ‘carbon farming’.

The ‘cost’ or ‘value’ of carbon is complex to quantify and differs hugely based on country or region and the method of calculation. The UK government, for example, prices a ton of carbon at a market value of £13.84 ($19.13) in 2020 (Department for Business, Energy and Industrial Strategy, 2019), whilst the European Union considers a ton of carbon to be worth €34.25 ($41.56) at the start of 2021 (Huang et al., 2021).
When the social cost, rather than market value, is considered, values are generally higher, ranging from $60 to $120 per ton. (Nordhaus, 2017) It has also recently been suggested that a homogenous cost of carbon globally is unrealistic, and that in actuality the price varies from $15 to more than $100 per ton, with Jordan falling in the range of $35-$55 per ton (Ricke et al., 2018). For this reason, a number of scenarios were defined for the quantification of ecosystem services potential.

As a consequence of the large variety of possible ecosystem services, there exists a great many approaches for their quantification. For this study, the integrated valuation of ecosystem services and trade-offs (inVEST) model suite was utilised. This model was selected due to its open source design, and the implicit focus on carbon sequestration in the set up (Natural Capital Project, 2019). The model is spatially explicit and uses a raster-based format.

4.5.2: Model Structure

The inVEST model calculates the storage of carbon based on land use type and carbon pools. It is a simpler model than RothC-26.3 with an assumption of linearity in the sequestration pathway. The advantage of the model is that values can be user assigned for land use types, and so it was possible to use the smaller scale RothC-26.3 estimates as inputs. The inVEST model then produces a raster map of the sequestration potential. From this map, the value of sequestered carbon can be given over time for a specified parcel *x* by *equation 6*;

$$value_{seq_x} = V \frac{sequest_x}{yr_{fut} - yr_{cur}} \sum_{t=0}^{yr_{fut} - yr_{cur} - 1} \frac{1}{(1+\frac{r}{100})^t \, (1+\frac{p}{100})^t} \tag{6}$$

Where *V* is the price per metric ton of carbon, *r* is the market discount in the price of carbon and *p* is the annual rate of change for the price of carbon. By using this equation, a monetary value was applied to the ecosystem service of carbon sequestration. Whilst an imperfect solution, monetary value is a widely utilised method of quantifying an ecosystem service (Lal, 2014; Estrada et al., 2015; Groshans et al., 2019).

4.5.3: Model Application

The model was applied to the Badia at a spatial resolution of 1km, as this was the resolution of the coarsest input layer. The primary input layer utilised was a land cover map of the region, combined with maps of soil content and topographic information. Output raster files were inspected and analysed outside of the inVEST architecture using the freely available software QGIS, as inVEST does not support viewing of the output files that it produces. Total carbon sequestration potential was quantified first, followed by the valuation of the carbon stocks. All results were given in units per pixel and then converted to per km^2 and per hectare values. In comparison to RothC-26.3, no treatment of climate is included in the inVEST model and the uncertainties involved in predicting carbon costs are too high to be useful, and so the effect of changing climate was not considered in the ecosystem service quantification portion of this project.

5: Results

5.1: Carbon Sequestration in a Single System

5.1.1: Inputs Calculation

As described in *4.4: Carbon Modelling*, some model inputs need calculation or transformation to be utilised in the format that the Roth-C model requires.

Vegetation cover data is shown below in *figure 5.1.1.1* for the pit furrow, ridge and interspace of the Vallerani system installed 2 years prior to field measurement, which was then resampled to monthly timesteps to be used in modelling (*table 5.1.1.1*). The shape of the curve present for each data set was also used to extrapolate coverage for the months where sampling was not completed (i.e. October, November, December and January).

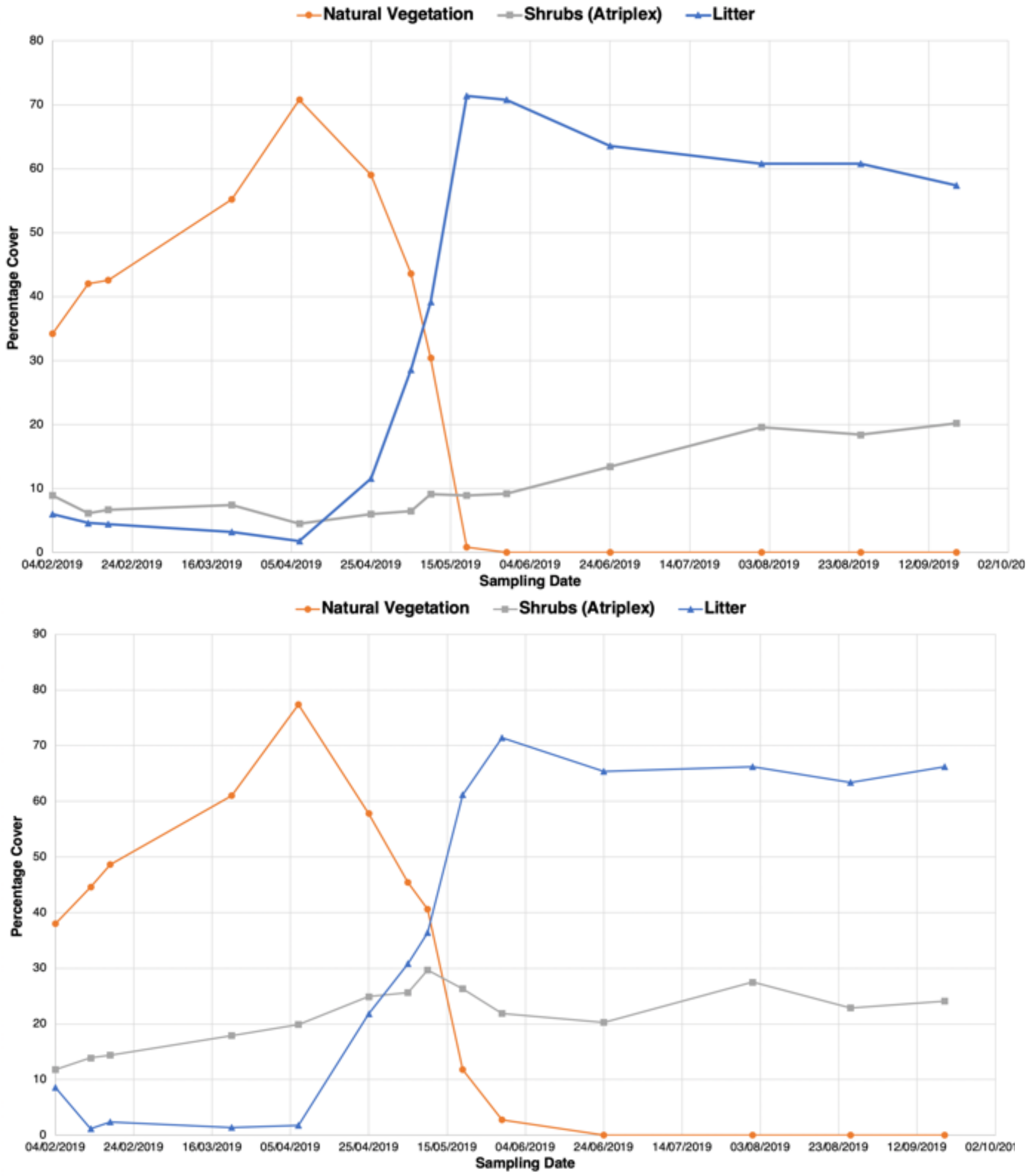


Figure 5.1.1.1: Changes in natural vegetation, planted shrubs and litter in a Vallerani furrow (top) and ridge (bottom). Data from Akimoto (2021).

As shown in these graphs, the pattern of vegetation cover was virtually identical in the furrow and ridge, albeit with slightly higher peak values for natural vegetation recorded at the ridge. For this reason, the same values for soil cover factor (c) (see *table 5.1.1.1* below) were utilised at both the ridge and furrow.

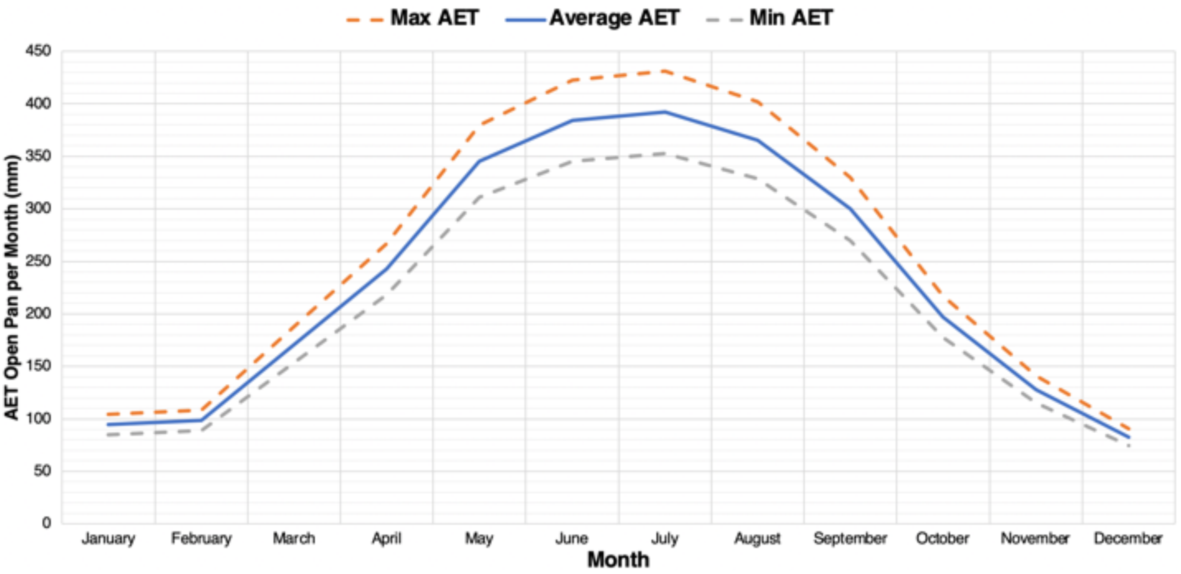
Table 5.1.1.1: Percentage cover (to the nearest 1%) for the three cover types in a Vallerani pit. Totals are used to determine the model soil cover factor (c). ^{1} excludes litter, ^{2} includes litter.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Natural	28	39	52	66	19	0	0	0	0	0	4	7
Shrub	9	8	7	6	9	13	16	18	19	16	15	12
***Total*^{1}**	*37*	*47*	*59*	*72*	*28*	*13*	*16*	*18*	*19*	*16*	*19*	*19*
Litter	11	5	4	10	53	65	63	62	60	52	27	15
***Total*^{2}**	*48*	*52*	*63*	*82*	*81*	*78*	*79*	*80*	*79*	*68*	*46*	*34*
c^1	1.0	1.0	1.0	1.0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
c^2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.6

Shrub coverage is much more consistent across the year than natural vegetation. The shape of the litter curve is similar to that of the natural vegetation, but peaks later in the year, as the majority of the litter is made up of dead and dying natural vegetation.

c^1 is utilised in this study, as growing vegetation alone (i.e. excluding litter) is considered to provide a more accurate soil cover factor in dryland soils (Gottschalk et al., 2012).

Open pan evaporation data was calculated using the method suggested by the Roth-C developers, which involves using mean monthly potential evaporation data from climatically similar locations and dividing by 0.75, necessary because the model internally multiplies the input data by 0.75 (Müller, 2012). Open pan evapotranspiration across the year is shown below in *figure 5.1.1.2*, along with the other climatological inputs, which are calculated from daily data recorded over the period 2010-2019 and averaged. Upper and lower bounds for evapotranspiration are set at 10%, as is usual when using this data (Price et al., 2007), and are set for precipitation and mean air temperature based on the extreme monthly values for each variable recorded at Queen Alia International Airport.



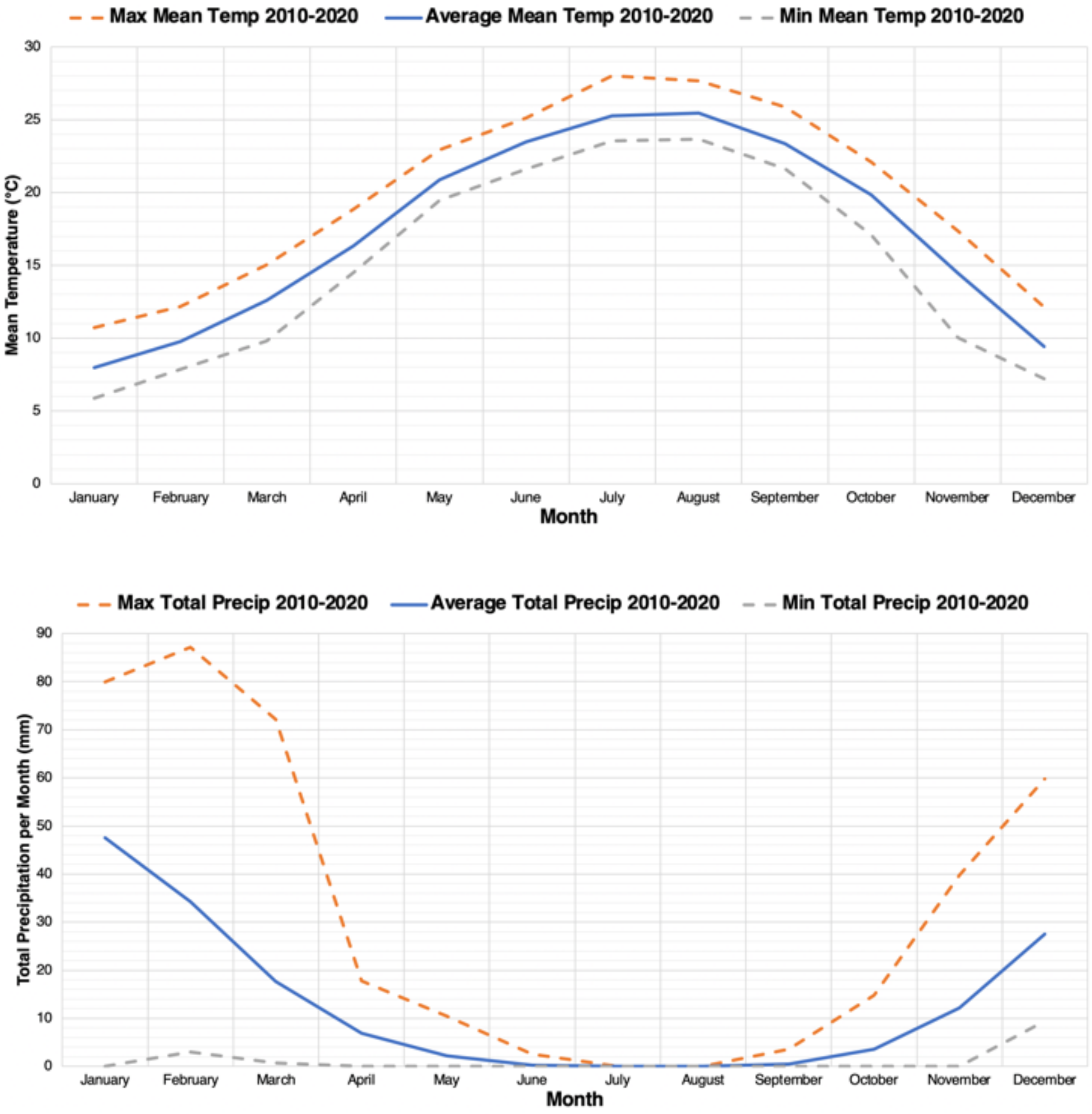


Figure 5.1.1.2: Climatological Model Inputs: Monthly total open pan evapotranspiration (previous page), mean air temperature (top) and monthly total precipitation (bottom). Temperature and precipitation from Queen Alia International Airport, evapotranspiration from Müller (2012).

Similarly, the carbon input to the system from animal waste required calculating from other available information. Goat and other small ruminant manure typically contains 250g of carbon per 1kg (Mnkeni and Austin, 2009), and a single animal produces between 0.37 (does) and 0.38kg (bucks) of manure per month in the wet season, and 0.34 (does) and 0.35kg (bucks) in the dry season (Osuhor et al., 2002). There are an estimated 10 small ruminants grazing per hectare in the area around the field site, dominantly in October to December, and although literature is sparse, local experts suggest that their waste remains in the interspace and enters the Vallerani furrow at a ratio of 1:10 (S. Strohmeier, personal communication 17th December 2020). Average manure input to the Vallerani furrow for a given month is therefore calculated from *equation 7,* and the result converted from kg C ha^{-1} to t C ha^{-1};

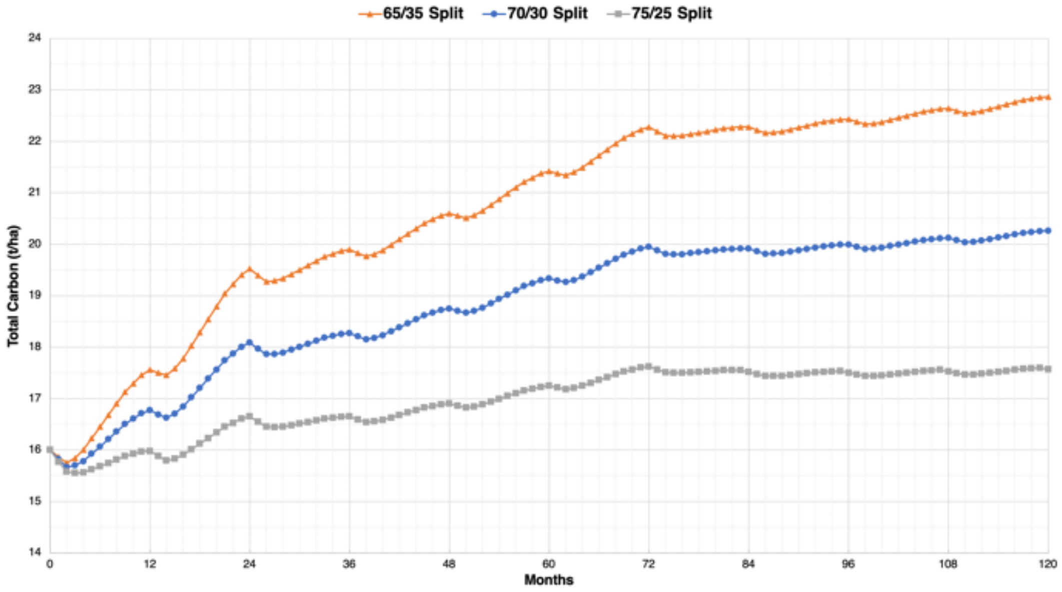
$$Monthly\ Input\ (kg\ C\ ha^{-1}) = \Big(\big(10 * 0.375(kg)\big) * 0.25\Big) * 0.9 \qquad (7)$$

There was more confidence in the results of the soil data inputs that were determined directly in the field (i.e. clay content, soil cover and soil layer depth), and so the creation of scenarios was unnecessary for these inputs. Finally, whilst we can be fairly confident in the measurements of above ground biomass made, the below ground portion has not been determined in the field. Reviews of the subject (e.g. Snyman, 2005; Ravindranath and Ostwald, 2007) consider below ground biomass to typically account for anywhere between 25 and 35% of the total biomass by weight in a dryland system, and so three biomass splits were utilised as scenarios in the modelling; 75/25, 70/30 and 65/35.

5.1.2: Sequestration Calculation

There was no difference between the outputs obtained from the three different weather scenarios outlined in *5.1.1: Inputs Calculation*. The reasons for this are twofold. Firstly, the soil is so extremely dry that the soil moisture conditions were considered to be no different from each other in the different climate input scenarios by the model. Secondly, as temperature is simplified to a rate modifying factor in the model, and all three of the climate input scenarios had average temperatures higher than the model's original tested range, all scenarios ended up with the same rate modifying factor as each other. Between these two points, the different climate input scenarios described essentially translated to the model as the exact same input, and therefore the same results.

Changing land management conditions, such as biomass and animal waste addition, however, can make a pronounced difference to the soil carbon stocks. As can be seen in *figure 5.1.2.1*, the difference between the results obtained under the three realistic biomass splits can be significant; an average of 17.45% between the highest (65/35 split) and lowest (75/25 split) values, and an average of 9.62% and 9.69% difference between the middle (70/30 split) and the maximum and minimum values respectively. The effect of changing farmyard manure is minimal, with all results within 3% of one another, likely due to the small percentage that the farmyard manure (goat waste) makes up of the total carbon provision.



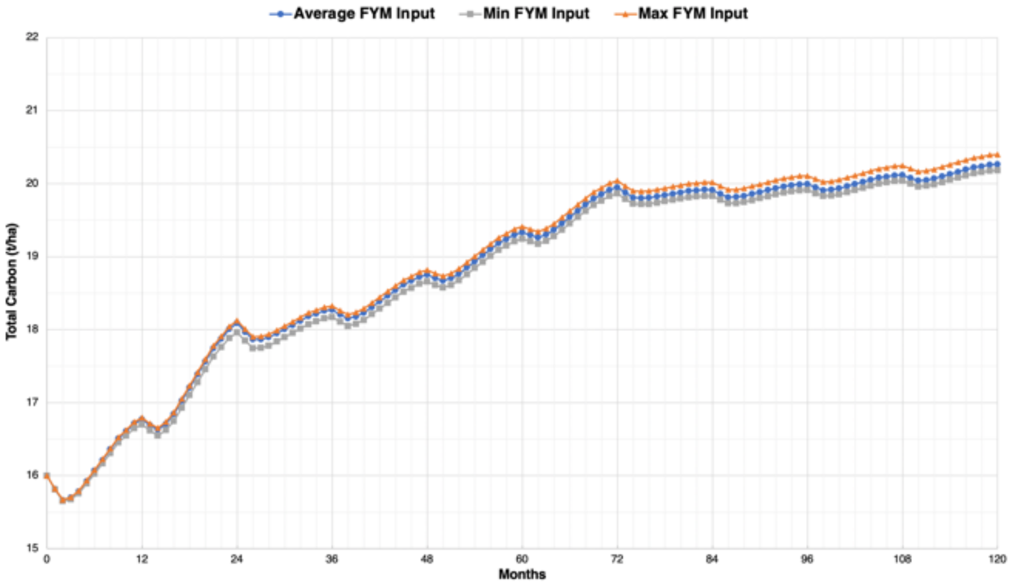


Figure 5.1.2.1: Impact of changing land management on total carbon in a Vallerani furrow. Results for changes to biomass splits (top) and farmyard manure input (bottom). Note different vertical axes scales and consistent horizontal axes.

Considering the variations outlined above, average scenarios were run for the Vallerani furrow and ridge and the interspace, the results of which can be seen in *figure 5.1.2.2*. From these scenarios, the total amount of carbon sequestration caused by the implementation of the Vallerani structures can be calculated.

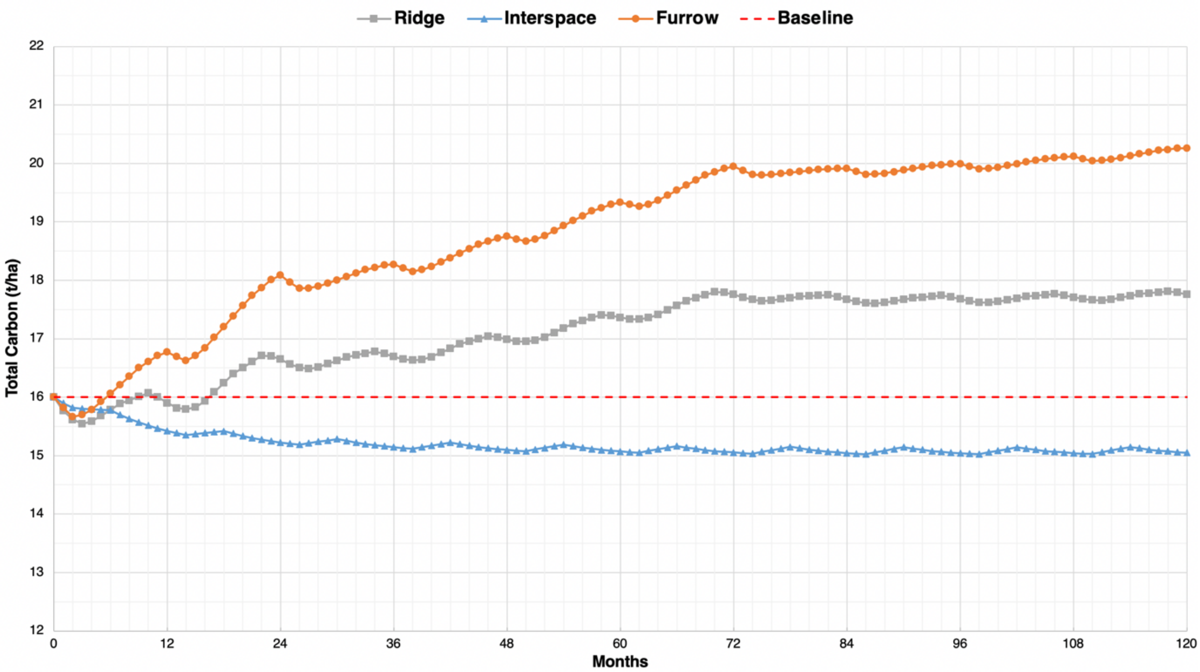


Figure 5.1.2.2: Total carbon over a 10-year period in the Vallerani furrow and ridge and interspace. Baseline is included to account for non-equilibrium conditions (see below).

The difference between results for the interspace and the furrow and ridge averages at 23.98% and 12.61%, respectively. Modelled values for the interspace, however, decrease at the beginning of the study as the internal model dynamics consider the carbon added insufficient to maintain soil carbon at 16 t/ha. Whilst some decrease in soil carbon is certainly possible in the untreated areas through soil degradation, the pace shown is likely, at least partly, a modelling artifact and so not realistic (Apesteguía et al., 2015). For this reason, a more cautious approach would consider the soil to be in equilibrium at the start of the study, and so calculate the impact of the Vallerani structures based on increase above 16 t C/ha.

Across the study period, this would mean that the furrow could be expected to sequester an additional 4.26 t/ha of carbon, and the ridge an additional 1.75 t/ha, or an increase in soil carbon storage of 17.65% and 6.90% respectively.

5.1.3: Result Verification

Initial conditions were verified using data collected from the field and laboratory procedures outlined in *4: Methodology*, alongside several sources of remote sensing data (Asner and Heidebrecht 2002; Batjes, 2006; Scharlemann et al., 2014). Field soil organic carbon measurements were then used to verify the modelled results. As show in *figure 5.1.3.1*, these measurements most closely correspond to the upper bound of the modelled results (i.e. a 65:35 above ground: below ground biomass split), which is shown in the figure as the top of the yellow section. It is suggested that field results may be higher than modelled results due to the potential for surface biomass to be included in these results, and thus double counted. This means that the average modelled results (blue dashed line) likely represent a conservative estimate of the total sequestration potential in the system.

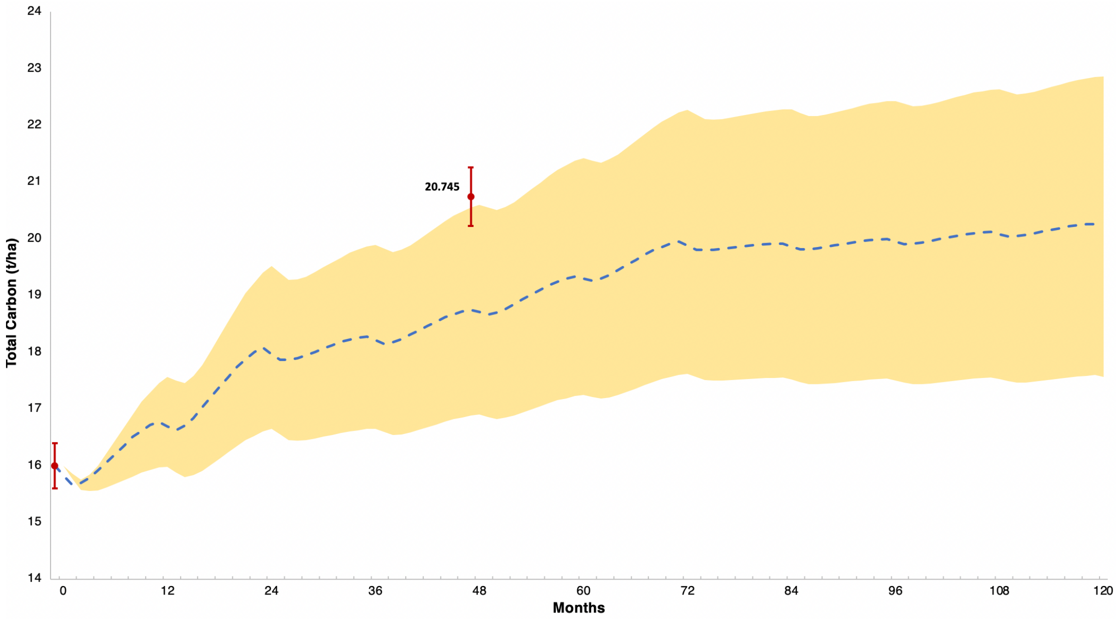


Figure 5.1.3.1: Upper and lower bounds for total carbon over a 10-year period in the Vallerani furrow, with dashed line representing the average modelled results. Points represents average measured data and error bar is equal to ±2.5%.

5.2: Carbon Sequestration at Larger Scales

5.2.1: Sequestration at the Catchment Scale

At the field site used for this study, 12 hectares of the 30 hectares are used for the Vallerani structures, and these 12 hectares are divided in area roughly 12% furrow, 8% ridge and 80% interspace, forming ~300 pits per hectare. Using these percentages to define a weighted-average result leads to a total sequestration potential of 0.65t C/ha across the 10-year period, or a total sequestration potential across the field site catchment of 7.9t C more than would be expected to occur naturally, without the influence of the Vallerani structures. Using the uncertainty already quantified, true results can be expected to be within 9.65% of these modelled results, or 7.9 ± 0.762 t C.

Whilst a small amount of carbon in absolute terms, this represents a large increase from the baseline conditions. This is especially promising when considering the marginal nature of the land concerned, where it has been repeatedly demonstrated that small changes to an ecosystem component can have outsized and profound effects on another component or the system as a whole (Lawrence et al., 2007; Mayor et al., 2019).

5.2.2: Sequestration at the Landscape Scale

Current carbon stocks were obtained from remote sensing data (Batjes, 2006; Scharlemann et al., 2014: Hengl et al., 2017) at a spatial resolution of 250m, and land cover from Al-Bakri et al., (2013). These values are established as relatively stable over the period 2000-2018 with changes to land cover types less than 1% per class across the entire period (Sarcinella, 2020). As shown in *figure 5.2.2.1*, however, there is spatial variation in both the initial carbon stocks and land cover across the Badia, which had to be accounted for when upscaling results.

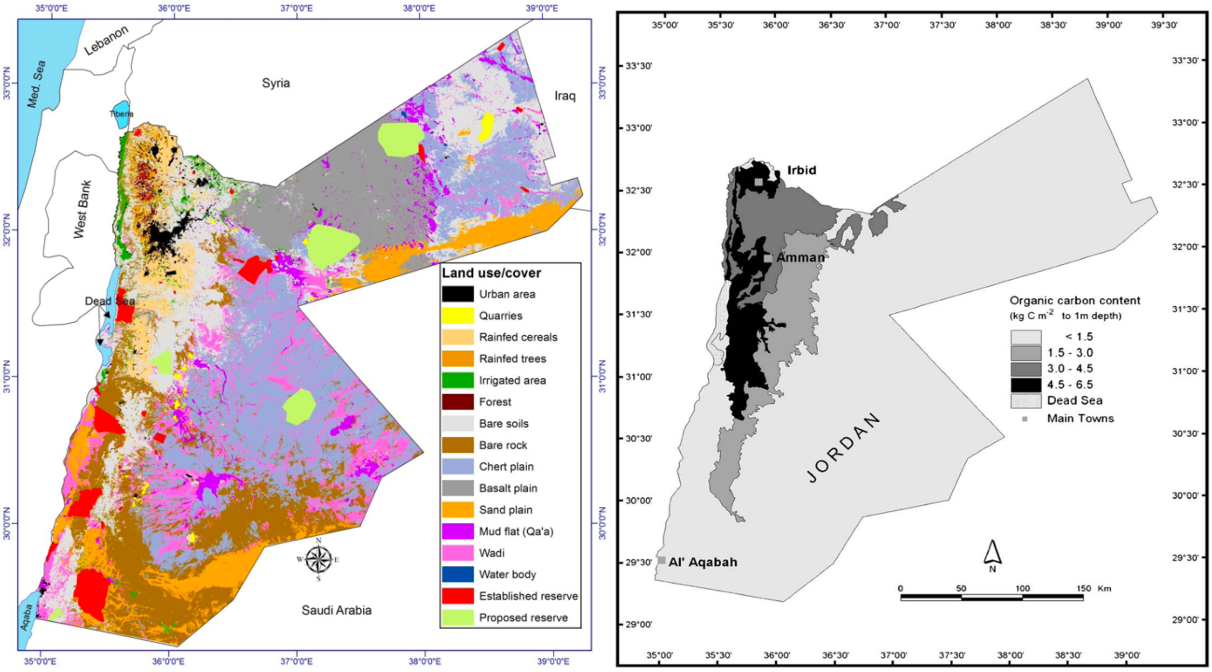


Figure 5.2.2.1: Land use/cover in Jordan defined from Sentinel data by Al-Bakri et al. (2013) (left) and soil carbon content from Batjes (2006) (right).

The suitably of land to be used for Vallerani implementation is established by ICARDA as having met all of the criteria outlined below in *table 5.2.2.1*.

Table 5.2.2.1: Suitability criteria for land to be used for Vallerani implementation

Criteria	**Units**	**Suitable Range**
Slope (s)	Degrees (°)	$s \leq 30$
Soil Depth (d)	Centimetre (cm)	$d \geq 50$
Soil Clay Content (l)	Percentage (%)	$l \leq 50$
Soil Sand Content (n)	Percentage (%)	$n \leq 50$
Soil Stone Content (e)	Percentage (%)	$e \leq 20$
Average Annual Precipitation (f)	Millimetre (mm)	$100 \leq f \leq 300$

In reality, the land must also be of a poor or marginal quality, as the use of developed urban or good quality farmland for Vallerani ploughing makes little economic sense. Using these criteria, and the maps shown in *figure 5.2.2.1*, a series of raster files was produced in collaboration with local experts (M. Haddad and S. Strohmeier, personal communication 3rd February 2021) leading to a map showing land areas theoretically suitable for Vallerani implementation across the entire Badia (*figure 5.2.2.2,* overleaf).

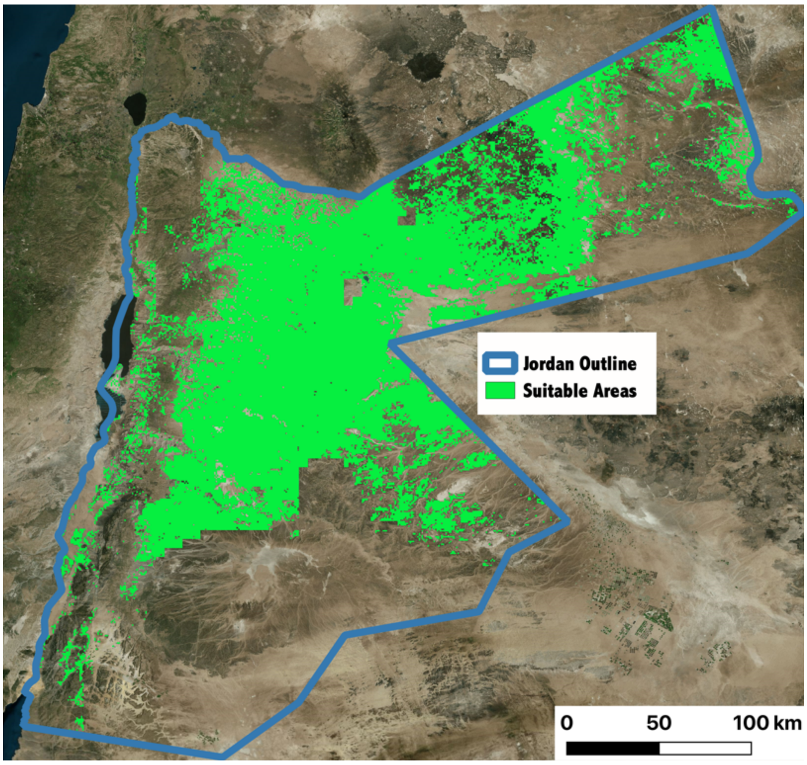


Figure 5.2.2.2: Areas suitable for Vallerani implementation according to the criteria outlined in *table 5.2.2.1*. Base map (satellite imagery) is open source.

Using this map, a total of 45,740km^2 (4,574,000 ha) of Jordan's 89,342km^2 (8,934,200 ha) total land area was considered suitable for Vallerani implementation, amounting to 51.20% of the country's total land area.

The results of the RothC modelling (*5.1-5.2.1*) showed that an increase in storage potential of 0.65 t C/ha. Scaled up across the Badia, this results in a total carbon storage potential of 2,973,100 tons in the top 30cm of soil, assuming that the ratio between furrow, pit and interspace for any given hectare remains as in the original field site; i.e. 3:2:20.

5.3: Ecosystem Services at the Landscape Scale

Using the raster files produced in *5.2.2: Sequestration at the Landscape Scale*, the inVEST model was used to produce a monetary estimate of the costs and benefits of using Vallerani systems to sequester carbon. Considering the uncertainty in carbon costs outlined above, the following carbon cost scenarios were defined;

Table 5.3.1: Scenarios for the cost of 1 ton of carbon, given in US dollars.

Scenario Name	Carbon Price ($/ton)
Market Value Low Estimate (1)	30
Market Value High Estimate (2)	55
Social Cost Low Estimate (3)	80
Social Cost High Estimate (4)	120

The costs incurred by implementing the structures were then considered. A Vallerani plough costs 68,000 JD and the specific tractor needed to pull the plough 132,000 JD, so a total equipment investment cost of 200,000 JD (~£207,000 or $286,000) is required (Akroush and Boubaker, 2015). Once this equipment is purchased (or loaned) the costs per hectare of implementing the structures is estimated to be around $95 inclusive of labour costs and auxiliary components (Vallerani System, 2013), with lower values expected if volunteer labour can be utilised. The results of this are shown below in *table 5.3.2*.

Table 5.3.2: Results of ecosystem services modelling for scenarios 1, 2 and 3 (see *table 5.3.1*)

Scenario	1	2	3	4
Carbon Price ($/ton)	30	55	80	120
Total Suitable Area (ha)	4,574,000			
Implementation Cost ($/ha)	95			
Total Carbon Sequestered (tons)	2,973,100			
Total Costs ($)	434,530,000			
Total Benefits ($)	89,193,000	163,520,500	237,848,000	356,772,000
Cost-Benefit Result ($)	*345,337,000*	*271,009,500*	*196,682,000*	*77,758,000*
Offset Cost ($/ha)	*75.50*	*59.25*	*43.00*	*17.00*

The uncertainty calculated in the field data and RothC modelling can also be assumed to propagate throughout the upscaling of results to the whole Badia and resultant ecosystem service modelling. If a consistent rate of 9.64% is continued, then total Badia-wide carbon stocks can vary by as much as ±286,606 tons, or an economic value of $8,598,205 under scenario 1 and $34,392,720 under scenario 4.

5.4: Considerations and Summary

There is confidence in the results gained from this study, however there are a few potential limitations which must be considered before drawing conclusions or making recommendations about Vallerani implementation. Firstly, in relation to the Roth-C modelling, it is clear that there are larger uncertainties in some of the model inputs than others. In particular, the differences between the results for the differing biomass splits is much larger than for changes to farmyard manure (goat waste), where the difference in values obtained can be considered insignificant. Secondly, inherent to the use of the Roth-C model is the issue that all values are considered at monthly time steps when in reality some values change on a much smaller timescale than this. For example, initial field sampling shows that vegetation cover varies over timescales of weeks rather than months, especially in the late spring (April and May).

Secondly, and perhaps more importantly, the way in which the model simplifies climate inputs must be considered. By simplifying these to a rate modifying factor, based on deviance from the initial development range (i.e. European agricultural soils), more extreme values are smoothed to the same rate modifying factor. This may cause some concerns about the validity of the results obtained. Using the model outside of its initial development range has, however, been widely shown to be valid, with small fluctuations in weather conditions, in the order of those used in this study, having a statistically insignificant impact on ground verified soil carbon dynamics (Robertson et al., 2018). In particular, the sporadic nature of rainfall in the drylands coupled with rapid drying means that soil moisture content remains consistently low at the monthly timescales utilised in the model. Several studies have demonstrated that the speed of carbon turnover is sufficiently slow for this spatial resolution to be sufficient, and therefore modelled results to be valid (Young et al., 2009: Darrouzet-Nardi et al., 2015).

The results gained from the inVEST (ecosystem service) modelling are extremely promising, demonstrating the potential for almost 3 million tonnes of carbon to be sequestered country wide in just 10 years. Whilst there are large ranges to the results obtained here, especially when assessing the economic costs of the Vallerani implementation, this is to be expected when considering the established uncertainty inherent across much of environmental economics (Pindyck, 2007).

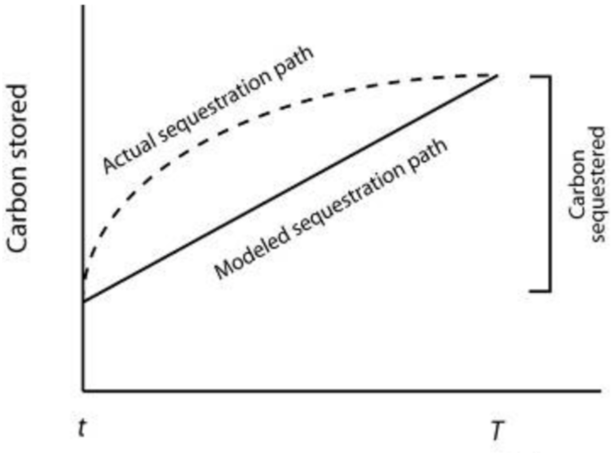


Figure 5.4.1: Sequestration pathways over time for the inVEST model and actual sequestration. RothC results more accurately represent the actual sequestration pathway. Figure from Natural Capital Project (2019)

Specific to the use of inVEST, it should also be noted that a linear sequestration pathway is assumed, which we know from the RothC model not to be accurate (*figure 5.4.1*). In the short term, this is likely to lead to significant underestimations of carbon sequestration, however the timescales for which inVEST has been used in this study are longer than the expected equilibrium timescales and so this effect is largely mitigated against, and considered sufficiently small to be ignored by most studies (Caruso et al., 2018; Gubler et al., 2019).

6: Discussion

6.1: Context and Implications

In accordance with established best practice guidance for reporting the economic potential of environmental interventions (see Iacona et al., 2018), the results of this study represent conservative likely outcomes. True values are likely to be somewhat higher once the following areas are quantified;

1) This study considers only the top 30cm of soil. It is highly likely that considering a deeper soil profile will lead to larger potential soil carbon storage, at least up to a depth of 65 to 80cm, and therefore greater economic benefit.
2) Economies of scale are not considered by this study, but in many scenarios a cost per unit (in this case hectare) falls as the number of units is increased. An implementation of water harvesting structures on the scale of the Jordanian Badia would be unprecedented, and as such it is very difficult to predict exactly how significant these cost reductions may be.
3) Temporal scale is limited, with the choice to focus the inVEST modelling on the same 10-year time period as the initial carbon dynamics modelling. Carbon turnover is a notoriously slow process, and so expanding the time of this project (which would be necessary anyway to allow such a large scale infrastructure project to be developed), would likely allow for significantly more carbon sequestration, even if the rate of storage continues to decrease over time, as this study has demonstrated.

Furthermore, even if there were no, or far smaller, regulating ecosystem services provided in terms of carbon sequestration, there is still a well-established increase in food production from the implementation of Vallerani systems. This in itself represents a hugely valuable provisioning ecosystem service to Jordan, and one that will only become more important as the country's population continues to grow. In particular, changing climate, coupled with a growing and increasingly urbanised and affluent population, is predicted to stretch resources in Jordan to their limits by 2050 (Koch et al., 2018). An inexpensive solution to these dual problems (food and water), with additional climate regulation benefits, is of paramount importance to ensuring the continued wellbeing of the Jordanian people. As well as ensuring sufficient food for people, healthier soil will produce better quality and more plentiful fodder for livestock, providing a benefit to farmers and to the wider population, who are almost certain to increase their demand for meat as the country develops (Wiedmann et al., 2020).

A wide variety of other ecosystem services can also be expected to increase by the widespread implementation of water harvesting structures, for example cultural services such as allowing the lifestyles of the Bedouin people to persist for longer than may otherwise have been possible and supporting services in the form of improved habitat provision.

When considering the feasibility of carbon sequestration as a means of economic growth and atmospheric CO_2 level reduction, there has been intense debate for close to 20 years (Brown and Adger, 1994; Ramakrishna et al, 2020). From a physical science perspective, some consider the dryland's degraded, carbon poor soils to have ample, and largely unexploited, potential for soil carbon storage (e.g. Glenn et al., 1993; Farage et al., 2003), whilst others consider this potential to be marginal at best, and totally unrealistic at worst (Van Groenigen et al., 2017). This study lends weight to the former argument, through the results generated by both RothC and inVEST modelling. This sequestration has the potential to have impacts on climate at a global scale; If 297,310 tons of carbon can be sequestered per year, as in this study, then this represents the removal of 4.84% of Jordan's annual 6,148,539 t C (22,772,370 t CO_2) total emissions (Spetan, 2016). With the established success of Vallerani systems in dryland regions across the world, there is also the potential for the structures to be used for soil carbon sequestration in other dryland regions across the Middle East and North Africa, further increasing the reduction in atmospheric CO_2.

More complicated, however, are debates surrounding the economic and ethical issues related to soil carbon sequestration and carbon credits. From an economic perspective, debate exists about the viability of utilising this technology, with some authors expressing concern that the long timescales involved in soil carbon sequestration, especially in dryland soils, means that variability of carbon price over time is often poorly constrained in feasibility studies, and the impact off fluctuating carbon price not given sufficient weight in considerations (Thamo et al, 2017; Paustian et al., 2019). Prices defined by the UK government, for example, are expected to increase from £12.76 ($17.63) to £80.83 ($111.67) in the period from 2018 to 2030 (Department for Business, Energy and Industrial Strategy, 2019). There is also the potential for such large-scale carbon sequestration availability to lower the price per ton of carbon, through the principle of supply and demand, which must be considered in a full economic appraisal of the costs and benefits of Vallerani implementation for carbon sequestration (Williams et al., 2005).

More specifically to the use of Vallerani structures in the sequestration of soil carbon, the reduction of efficiency in the structure must be considered in economic assessments. This study has based the reduction in efficiency on Gammoh and Oweis' (2011) view that the efficiency of a Vallerani pit reduces over time with relation to its water harvesting potential so that the capacity is approaching zero with between 10 and 30 years of use, and that it is reasonable to assume that some degradation will also occur with relation to carbon sequestration potential. Testing this assumption, however, will require longer term field studies beyond the scope of this project, and if the reduction is shown to be significantly different to the scenarios utilised in this study, then changes must be made to model scenarios to account for this at longer timescales- for example it is unknown at this stage if the original furrow will behave like the Vallerani ridge once it has filled, or if the system will trend back towards original conditions. At the very least, the economic cost of reinstalling pits, which may also change with time, (i.e. ploughing equipment, labour costs etc.) must be considered in any assessment of the economic viability of using Vallerani water harvesting structures to sequester carbon.

From an ethical, or environmental justice, perspective, there also exist several concerns. Firstly, the question of whether the damage likely to be wrought by climate change can be expressed in monetary terms to begin with is contested (Aldred, 2012). Secondly, many question if allowing any entity (be it a national government or private company) to avoid its responsibility to the environment based on its ability to pay can be considered ethically right (Page, 2013). Finally, there are those who are concerned by the perceived neo-colonial nature of carbon trading, whereby the global North essentially, wittingly or unwittingly, uses carbon trading as a method of perpetrating entrenched inequality between themselves and the global south (Lejano et al., 2020).

6.2: Further Research

Ultimately, these issues will require further study. It is acknowledged that a 'one size fits all' approach to the issue of carbon sequestration and carbon credits trading is inappropriate. This study can confidently demonstrate the scientific feasibility of soil carbon sequestration in the Jordanian Badia, and has made recommendations as to the potential economic, social and environmental benefits of following this approach. Further consideration of economic externalities and ethical concerns should be applied on a case by case study, both within Jordan and other dryland regions. If Vallerani structures are decided upon as an implementable solution, it is likely some financial help will have to be provided by governmental or non-governmental organisations (NGO's) in order to meet the high initial costs of equipment, which are more than ten times the average annual salary in the country, and therefore likely to represent a large barrier to adoption of the scheme.

Further work must also consider the effect of climate change on the quantification that this study has completed. As well as likely decreases in precipitation and increases in temperature, there will likely be a series of resultant changes to land use in the complex environmental system that forms the drylands. These include, but are not limited to, decreasing biomass input from plants, changing patterns of goat movement and therefore waste input, and the potential for abandonment of some land altogether. Modelling these changes will represent a complex challenge to overcome, due to large uncertainty ranges in prediction of tropical drylands precipitation of up to 40% and other uncertainties inherent in the predicting of the climate system over decades to centuries timescales (Ramaraj and Geethalakhimi, 2014).

7: Conclusions

The use of Vallerani structures is well established as a method of decreasing water scarcity in dryland regions. This study investigated the potential for these structures to also sequester carbon in the soil; a method of both increasing the health and productivity of the soil and also reducing atmospheric carbon (CO_2) levels. The results of this investigation are summarised below according to the objectives identified in *1: Introduction*.

1) *Quantifying the potential carbon sequestration of a single Vallerani system*
   In a single system, a Vallerani furrow can be expected to sequester an additional 4.26 t/ha of carbon over a ten-year period, whilst the Vallerani ridge can be expected to sequester a more modest 1.75 t/ha. This represents an increase of 17.65% and 6.9% on baseline conditions respectively. The main sources of uncertainty in these calculations are around the way in which biomass is split between above and below ground sources.

2) *Upscaling these results to assess how much carbon can be sequestered in larger scale water harvesting schemes, at both the whole catchment (km) and whole landscape/ Badia (100's km) scale*
   At the catchment scale, the field site is expected to sequester an additional 7.9 tons of carbon over a ten-year period when compared to baseline conditions. It is possible that this value may in actuality be larger, depending on the extent of soil carbon loss from the baseline conditions caused by land degradation. At the landscape scale of the whole Badia, almost 3 million tons of soil carbon can expect to be sequestered over a 10-year period if Vallerani structures were to be implemented everywhere that the land was suitable for them.

3) *Assessing the costs and benefits (ecosystem services) associated with the implementation of these systems at the whole Badia scale*
   The economic costs and benefits of soil carbon sequestration at this scale are both large and difficult to quantify, with the different scenarios in this study estimating the cost per hectare to range anywhere from \$17 to \$82. When considering the abundance of other ecosystem services offered by implementing these structures, however, it is likely that this apparent marginal cost may actually represent a benefit. When compared to the results of the first two objectives, there are larger uncertainties here, and a greater need for further study in the field.

Overall, the results of this study suggest that soil carbon sequestration can be successful at a variety of spatial scales. Further work should focus on constraining the effects of both climate change and fluctuating carbon prices on the results presented and expanding the simulations to longer temporal scales.

References

Abu-Awwad, A.M., Al-Bakri, J.T. and Alfawwaz, M.M., **2017**. Soil surface wetting pattern under trickle source in arid lands: badia regions. *Jordan Journal of Agricultural Sciences*, 405(5315), pp.1-11.

Adeel, Z., **2003**. Sustainable management of marginal drylands. *UNU Desertification Series*, (5).

Akimoto, K. **2021**. Interactions between soil properties, soil moisture conditions and vegetation recovery status at the MCWH adopted sites in Jordan's Badia (MSc Thesis). Tottori University, Tottori, Japan.

Akroush, S., & Boubaker, D., **2015**. Predicted Willingness of Farmer to Adopt Water Harvesting Technologies: A Case Study from the Jordanian Badia (Jordan). *American-Eurasian Journal of Agricultural & Environmental Science*, pp. 1502-1513.

Al-Adamat, R., Rawajfih, Z., Easter, M., Paustian, K., Coleman, K., Milne, E., Falloon, P., Powlson, D.S. and Batjes, N.H., **2007**. Predicted soil organic carbon stocks and changes in Jordan between 2000 and 2030 made using the GEFSOC Modelling System. *Agriculture, Ecosystems & Environment*, 122(1), pp.35-45.

Al-Bakri, J.T., Taylor, J.C. and Brewer, T.R., **2001**. Monitoring land use change in the Badia transition zone in Jordan using aerial photography and satellite imagery. *Geographical Journal, 167*(3), pp.248-262.

Al-Bakri, J.T., Salahat, M., Suleiman, A., Suifan, M., Hamdan, M.R., Khresat, S. and Kandakji, T., **2013**. Impact of climate and land use changes on water and food security in Jordan: Implications for transcending "the tragedy of the commons". *Sustainability*, 5(2), pp.724-748.

Aldred, J., **2012**. The ethics of emissions trading. *New Political Economy*, 17(3), pp.339-360.

Ali, A. and Yazar, A., **2007**. Effect of micro-catchment water harvesting on soil-water storage and shrub establishment in the arid environment*. International Journal of Agriculture & Biology*, 9(2), pp.302-306.

Al Naber, M. and Molle, F., **2016**. The politics of accessing desert land in Jordan. *Land Use Policy*, 59, pp.492-503.

Amundson, R. and Biardeau, L., **2018**. Opinion: Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings of the National Academy of Sciences*, 115(46), pp.11652-11656.

Apesteguía, M., Virto, I., Orcaray, L., Enrique, A. and Bescansa, P., **2015**. Effect of the conversion to irrigation of semiarid Mediterranean dryland agrosecoystems on soil carbon dynamics and soil aggregation. *Arid Land Research and Management*, 29(4), pp.399-414.

Asner, G.P. and Heidebrecht, K.B., **2002**. Spectral unmixing of vegetation, soil and dry carbon cover in arid regions: comparing multispectral and hyperspectral observations. *International Journal of Remote Sensing*, 23(19), pp.3939-3958.

Batjes, N.H., **2006**. Soil carbon stocks of Jordan and projected changes upon improved management of croplands. *Geoderma*, 132(3-4), pp.361-371.

Berrahmouni, N., Del Lungo, A. and Vallerani., A. **2017***. Forest and landscape restoration mechanisms, good practice*. FAO.

Bille, M., **2012**. Assembling heritage: investigating the UNESCO proclamation of Bedouin intangible heritage in Jordan. *International Journal of Heritage Studies*, 18(2), pp.107-123.

Bowman, G.M and Hutka, J., **2002**. Particle Size Analysis. *In Soil Physical Measurement and Interpretation for Land Evaluation* (Eds McKenzie, N., Coughlan, K. and Cresswell, H.) CSIRO Publishing: Victoria, pp 224-239.

Brown, K. and Adger, W.N., **1994**. Economic and political feasibility of international carbon offsets. *Forest Ecology and Management*, 68(2-3), pp.217-229.

Caruso, T., De Vries, F.T., Bardgett, R.D. and Lehmann, J., **2018**. Soil organic carbon dynamics matching ecological equilibrium theory. *Ecology and Evolution*, 8(22), pp.11169-11178.

Caulfield, M.E., Hammond, J., Fonte, S.J. and van Wijk, M., **2020**. Land tenure insecurity constrains cropping system investment in the Jordan Valley of the West Bank. *Sustainability*, 12(16), pp.6557-6575.

Coleman, K. and Jenkinson, D.S., **1996**. RothC-26.3-A Model for the turnover of carbon in soil. In *Evaluation of soil organic matter models*. Springer, Berlin, Heidelberg, pp. 237-246.

Cornelis, W.M., Araya, T., Wildermeersch, J., Mloza-Banda, M.K., Waweru, G., Obia, A., Verbist, K. and Boever, D., **2013**. Building resilience against drought: the soil-water perspective. *Desertification and Land degradation: Processes and Mitigation*, pp.1-15.

Critchley, W., Siegert, K., Chapman, C. and Finket, M., **2013**. *Water harvesting: A manual for the design and construction of water harvesting schemes for plant production*. Jodhpur, India; Scientific Publishers, pp. 53-124.

Darrouzet-Nardi, A., Reed, S.C., Grote, E.E. and Belnap, J., **2015**. Observations of net soil exchange of CO 2 in a dryland show experimental warming increases carbon losses in biocrust soils. *Biogeochemistry*, 126(3), pp.363-378.

Department for Business, Energy and Industrial Strategy., **2019**. Updated short-term traded carbon values used for UK public policy appraisal. *UK Government White Paper*. Accessed at: https://www.gov.uk/government/publications/updated-short-term-traded-carbon-values-used-for-uk-policy-appraisal-2018 [Accessed 09/02/21].

Diez, D.M., Barr, C., D and Cetinkaya-Rund, M. **2017.** OpenIntro Statistics (3rd ed.) Accessed at: https://www.openintro.org/stat/textbook.php [31/10/20].

Doocy, S., Sirois, A., Anderson, J., Tileva, M., Biermann, E., Storey, J.D. and Burnham, G., **2011**. Food security and humanitarian assistance among displaced Iraqi populations in Jordan and Syria. *Social Science & Medicine*, 72(2), pp.273-282.

Dregne, H.E., **2002**. Land degradation in the drylands*. Arid land research and management*, 16(2), pp.99-132.

El Kharraz, J., El-Sadek, A., Ghaffour, N. and Mino, E., **2012**. Water scarcity and drought in WANA countries. *Procedia Engineering*, 33, pp.14-29.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N. and Eisner, S., **2014**. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, 111(9), pp.3239-3244.

Estrada, G.C.D., Soares, M.L.G., Fernadez, V. and de Almeida, P.M.M., **2015**. The economic evaluation of carbon storage and sequestration as ecosystem services of mangroves: a case study from southeastern Brazil. *International Journal of Biodiversity Science, Ecosystem Services & Management,* 11(1), pp.29-35.

Falloon, P., Jones, C.D., Cerri, C.E., Al-Adamat, R., Kamoni, P., Bhattacharyya, T., Easter, M., Paustian, K., Killian, K., Coleman, K. and Milne, E., **2007**. Climate change and its impact on soil and vegetation carbon storage in Kenya, Jordan, India and Brazil. *Agriculture, Ecosystems & Environment*, 122(1), pp.114-124.

Farage, P., Pretty, J. and Ball, A., **2003**. Biophysical aspects of carbon sequestration in drylands. University of Essex.

Farage, P.K., Ardö, J., Olsson, L., Rienzi, E.A., Ball, A.S. and Pretty, J.N., **2007**. The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: A modelling approach. *Soil and Tillage research*, 94(2), pp.457-472.

Farina, R., Coleman, K. and Whitmore, A.P., **2013**. Modification of the RothC model for simulations of soil organic C dynamics in dryland regions. *Geoderma*, 200, pp.18-30.

Feng, S. and Fu, Q., **2013.** Expansion of global drylands under a warming climate. *Atmos. Chem. Phys*, 13(10), pp.81-110.

Gammoh, I.A. and Oweis, T.Y., **2011**. Performance and adaptation of the Vallerani mechanized water harvesting system in degraded Badia rangelands. *Journal of Environmental Science and Engineering*, 5(10), pp.1370-1380.

Ghazal, M., **2016**. Population stands at around 9.5 million, including 2.9 million guests. *The Jordan Times*. Accessed at www.jordantimes.com/news/local/population-stands-around-95-million-including-29-million-guests [3/10/20].

Gillabel, J., CebrIan-Lopez, B., Six, J. and Merckx, R., **2010**. Experimental evidence for the attenuating effect of SOM protection on temperature sensitivity of SOM decomposition. *Global Change Biology*, 16(10), pp.2789-2798.

Glenn, E., Squires, V., Olsen, M. and Frye, R., **1993.** Potential for carbon sequestration in the drylands. In *Terrestrial biospheric carbon fluxes quantification of sinks and sources of CO2.* Springer, Dordrecht, pp. 341-355.

Goldstein, J.H., Caldarone, G., Duarte, T.K., Ennaanay, D., Hannahs, N., Mendoza, G., Polasky, S., Wolny, S. and Daily, G.C., **2012**. Integrating ecosystem-service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences*, 109(19), pp.7565-7570.

Gottschalk, P., Smith, J.U., Wattenbach, M., Bellarby, J., Stehfest, E., Arnell, N., Osborn, T.J., Jones, C. and Smith, P., **2012**. How will organic carbon stocks in mineral soils evolve under future climate?: Global projections using RothC for a range of climate change scenarios. *Biogeosciences,* 9, pp.3151-3171.

Groshans, G.R., Mikhailova, E.A., Post, C.J., Schlautman, M.A. and Zhang, L., **2019**. Determining the value of soil inorganic carbon stocks in the contiguous United States based on the avoided social cost of carbon emissions. *Resources*, 8(3), pp.119-134.

Gubler, A., Wächter, D., Schwab, P., Müller, M. and Keller, A., **2019**. Twenty-five years of observations of soil organic carbon in Swiss croplands showing stability overall but with some divergent trends. *Environmental Monitoring and Assessment*, 191(5), pp.1-17.

Helldén, U., **1991**. Desertification: time for an assessment?. *Ambio*, pp.372-383.

Hengl, T., Leenaars, J.G., Shepherd, K.D., Walsh, M.G., Heuvelink, G.B., Mamo, T., Tilahun, H., Berkhout, E., Cooper, M., Fegraus, E. and Wheeler, I., **2017**. Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. *Nutrient Cycling in Agroecosystems*, 109(1), pp.77-102.

Hoekstra, A.Y. and Chapagain, A.K., **2006**. Water footprints of nations: water use by people as a function of their consumption pattern. In *Integrated assessment of water resources and global change*. Springer, Dordrech, pp. 35-48.

Homyak, P.M., Blankinship, J.C., Marchus, K., Lucero, D.M., Sickman, J.O. and Schimel, J.P., **2016**. Aridity and plant uptake interact to make dryland soils hotspots for nitric oxide (NO) emissions. *Proceedings of the National Academy of Sciences*, 113(19), pp.E2608-E2616.

Huang, Y., Dai, X., Wang, Q. and Zhou, D., **2021**. A hybrid model for carbon price forecasting using GARCH and long short-term memory network. *Applied Energy*, 285, p.116485.

Iacona, G.D., Sutherland, W.J., Mappin, B., Adams, V.M., Armsworth, P.R., Coleshaw, T., Cook, C., Craigie, I., Dicks, L.V., Fitzsimons, J.A. and McGowan, J., **2018**. Standardized reporting of the costs of management interventions for biodiversity conservation. *Conservation Biology*, 32(5), pp.979-988.

James, J.J., Sheley, R.L., Erickson, T., Rollins, K.S., Taylor, M.H. and Dixon, K.W., **2013**. A systems approach to restoring degraded drylands. *Journal of Applied Ecology*, 50(3), pp.730-739.

Jastrow, J.D., Amonette, J.E. and Bailey, V.L., **2007**. Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. *Climatic Change*, 80(1-2), pp.5-23.

Jenkinson D.S., Hart P.B.S., Rayner J.H. and Parry L.C., **1987**. Modelling the turnover of organic matter in long-term experiments at Rothamsted*. INTECOL Bulletin* 15, pp.1-8.

Jenkinson D.S., Harkness D.D., Vance E.D., Adams D.E. and Harrison A.F., **1992**. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. *Soil Biology & Biochemistry* 24(4), pp.295-308.

Jenkinson, D.S., Meridith, J., Kinyamario, J.I., Warren, G.P., Wong, M.T.F., Harkness, D.D., Bol, R. and Coleman, K., **1999**. Estimating net primary production from measurements made on soil organic matter. *Ecology* 80, 2762–2773.

Johns, C., **2017**. Measuring soil carbon and soil carbon change. *Strategic Analysis Paper: Independent Strategic Analysis of Australia's Global Interests*.

Jordanian Department of Statistics, **2015**. General Population and Housing Census. Accessed at http://dosweb.dos.gov.jo [7/10/20].

Kamai, T., Weisbrod, N. and Dragila, M.I., **2009**. Impact of ambient temperature on evaporation from surface-exposed fractures. *Water Resources Research*, 45(2), pp.2417-2428.

Karrou, M., Oweis, T., Ziadat, F. and Awawdeh, F., **2011**. Rehabilitation and integrated management of dry rangelands environments with water harvesting. *Community-based optimization of the management of scarce water resources in agriculture in CWANA Report*, (9) pp.1-202.

Kelland, M.E., Wade, P.W., Lewis, A.L., Taylor, L.L., Sarkar, B., Andrews, M.G., Lomas, M.R., Cotton, T.A., Kemp, S.J., James, R.H. and Pearce, C.R., **2020**. Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*, 26(6), pp.3658-3676.

Khresat, S.A., Rawajfih, Z. and Mohammad, M., **1998**. Land degradation in north-western Jordan: causes and processes. *Journal of Arid Environments*, 39(4), pp.623-629.

Koch, J., Wimmer, F. and Schaldach, R., **2018**. Analyzing the relationship between urbanization, food supply and demand, and irrigation requirements in Jordan. *Science of the Total Environment*, 636, pp.1500-1509.

Lal, R., H. M. Hassan, and J. Dumanski. **1999**. Desertification control to sequester C and mitigate the greenhouse effect. In N. J. Rosenberg, R. C. Izaurralde, and E. L. Malone. (Eds), *Carbon sequestration in soils: science, monitoring and beyond*. Battelle Press, Columbus, Ohio., pp. 83–151.

Lal, R., **2004**. Carbon sequestration in dryland ecosystems. *Environmental Management*, 33(4), pp.528-544.

Lal., R., **2008**. Carbon sequestration. *Philosophical Transactions of the Royal Society B* 363, pp.815-830.

Lal, R., **2014.** Societal value of soil carbon. *Journal of Soil and Water Conservation*, 69(6), pp.186A-192A.

Lawrence, D., D'Odorico, P., Diekmann, L., DeLonge, M., Das, R. and Eaton, J., **2007**. Ecological feedbacks following deforestation create the potential for a catastrophic ecosystem shift in tropical dry forest. *Proceedings of the National Academy of Sciences*, 104(52), pp.20696-20701.

Lejano, R.P., Kan, W.S. and Chau, C.C., **2020**. The Hidden Disequities of Carbon Trading: Carbon Emissions, Air Toxics, and Environmental Justice. *Frontiers in Environmental Science* (8), pp.1-6.

Malagnoux, M. **2008**. Degraded Arid Land Restoration for Afforestation and Agro-Silvo-Pastoral Production through New Water Harvesting Mechanized Technology. *The Future of Dry Lands*, pp.269-282.

Marques, A.C., Fuinhas, J.A. and Pais, D.F., **2018**. Economic growth, sustainable development and food consumption: Evidence across different income groups of countries. *Journal of Cleaner Production*, 196, pp.245-258.

Mayor, A.G., Bautista, S., Rodriguez, F. and Kéfi, S., **2019**. Connectivity-mediated ecohydrological feedbacks and regime shifts in drylands. *Ecosystems*, 22(7), pp.1497-1511.

Mazahreh, S., Alkharabsheh, M., Bsoul, M., Hammor, D.A. and Al Mahasneh, L., **2018**. Identification and Mapping of Hot Spot Areas Susceptible to Soil Erosion in Erak Al karak Area Using Geoinformatics. *International Journal of Research-Granthaalayah*, 6(6), pp.246-259.

McCarl, B.A. and Schneider, U.A., **2001**. Greenhouse gas mitigation in US agriculture and forestry. *Science*, 294(5551), pp.2481-2483.

Mitsch, W.J. and Jørgensen, S.E., **2003**. *Ecological engineering and ecosystem restoration*. John Wiley & Sons., pp.23-40.

Mnkeni, P.N.S. and Austin, L.M., **2009**. Fertiliser value of human manure from pilot urine-diversion toilets. *Water SA*, 35(1), pp.133-140.

Muller, M.J., **2012**. *Selected climatic data for a global set of standard stations for vegetation science* (Vol. 5). Springer Science & Business Media. pp. 223-269.

Müller, T. and Höper, H., **2004**. Soil organic matter turnover as a function of the soil clay content: consequences for model applications. *Soil Biology and Biochemistry*, 36(6), pp.877-888.

Nature Capital Project, **2019**. Carbon Storage and Sequestration-InVEST 3.8.9 User Guide. Accessed at http://releases.naturalcapitalproject.org/invest-userguide [1/11/20]

Nicholson, S. E., **2011**. 'Introduction to dryland environments' in *Dryland climatology*. Cambridge; Cambridge University Press, pp.3-5.

Nordhaus, W.D., **2017**. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7), pp.1518-1523.

Ontl, T. A. & Schulte, L. A. **2012.** Soil Carbon Storage. *Nature Education Knowledge* 3(10):35

Osuhor, C.U., Alawa, J.P. and Akpa, G.N., **2002**. Research note: Manure production by goats grazing native pasture in Nigeria. *Tropical Grasslands*, 36(2), pp.123-125.

Oweis, T., & Hachum, A., **2006**. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management*, 80., pp. 57-73.

Oweis, T.Y., **2017**. Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: a conceptual review of opportunities and constraints in a changing climate. *Environmental Reviews*, 25(2), pp.135-149.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P. and Dubash, N.K., **2014**. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. IPCC.

Page, E.A., **2013**. The ethics of emissions trading. *Wiley Interdisciplinary Reviews: Climate Change*, 4(4), pp.233-243.

Paustian, K., Larson, E., Kent, J., Marx, E. and Swan, A., **2019**. Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate*, 1, pp.8-19.

Pindyck, R.S., **2007**. Uncertainty in environmental economics. Review of Environmental Economics and Policy, 1(1), pp.45-65.

Price, R.M., Nuttle, W.K., Cosby, B.J. and Swart, P.K., **2007**. Variation and uncertainty in evaporation from a subtropical estuary: Florida Bay. *Estuaries and Coasts*, 30(3), pp.497-506.

Ramakrishna, W., Rathore, P., Kumari, R. and Yadav, R., **2020**. Brown gold of marginal soil: Plant growth promoting bacteria to overcome plant abiotic stress for agriculture, biofuels and carbon sequestration. *Science of The Total Environment*, 711, pp.135062-135069.

Ramaraj, A.P and Geethalkshmi, V., **2014**. Analysing the uncertainty in climate projected by RCP 4.5 over Coimbatore. *Eco. Env & Cons.* 20(3), pp.125-128.

Ravindranath, N.H. and Ostwald, M., **2007**. *Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects* (Vol. 29). Springer Science & Business Media, pp. 149-156.

Reid, W.V., Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A.K., Hassan, R. and Kasperson, R., **2005**. *Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment*. Island Press.

Ricke, K., Drouet, L., Caldeira, K. and Tavoni, M., **2018**. Country-level social cost of carbon. *Nature Climate Change*, 8(10), pp.895-900.

Robertson, A.D., Zhang, Y., Sherrod, L.A., Rosenzweig, S.T., Ma, L., Ahuja, L. and Schipanski, M.E., **2018.** Climate change impacts on yields and soil carbon in row crop dryland agriculture. *Journal of Environmental Quality*, 47(4), pp.684-694.

Salem, B.B., **1989**. *Arid zone forestry: a guide for field technicians* (No. 20). Food and Agriculture Organization (FAO).

Sarcinella, M., **2020**. Desertification assessment of the Jordan Badia using remote sensing technology (MSc Thesis). Utrecht University, Utrecht, Netherlands. Accessed at dspace.library.uu.nl/handle/1874/397788.

Scharlemann, J.P., Tanner, E.V., Hiederer, R. and Kapos, V., **2014**. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management*, 5(1), pp.81-91.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A. and Whitford, W.G., **1990**. Biological feedbacks in global desertification. *Science*, 247(4946), pp.1043-1048.

Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S. and Schmidt, S., **2011**. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. *Journal of Applied Ecology*, 48(3), pp.630-636.

Shawahneh, N., Saoub, H., Oweis, T., Haddad, N. and Karrou, M., **2011**. Impact of microcatchment water harvesting on the diversity of the Badia rangelands of Jordan. *Rehabilitation and integrated management of dry rangelands environments with water harvesting*, pp.85-92

Sleutel, S., De Neve, S., Hofman, G., Boeckx, P., Beheydt, D., Van Cleemput, O., Mestdagh, I., Lootens, P., Carlier, L., Van Camp, N. and Verbeeck, H., **2003**. Carbon stock changes and carbon sequestration potential of Flemish cropland soils. *Global Change Biology*, 9(8), pp.1193-1203.

Smith, M., Allen, R., and Pereira, L., **1998.** Revised FAO methodology for crop-water requirements. *No. IAEA-TECDOC.*, pp.1016-1048.

Smith, P., **2004**. How long before a change in soil organic carbon can be detected?. *Global Change Biology*, 10(11), pp.1878-1883.

Snyman, H.A., **2005**. Rangeland degradation in a semi-arid South Africa—I: influence on seasonal root distribution, root/shoot ratios and water-use efficiency. *Journal of Arid Environments*, 60(3), pp.457-481.

Sparling G.P., Cheshire M.V and Mundie C.M., **1982**. Effect of barley plants on the decomposition of 14C-labelled soil organic matter. *Journal of Soil Science* 33, pp. 89-100.

Spetan, K.A.A.A., **2016**. Renewable energy consumption, CO2 emissions and economic growth: A case of Jordan. *International Journal of Business and Economics Research*, 5(6), pp.217-226.

Sterk, G. and Stoorvogel, J.J., **2020**. Desertification—Scientific Versus Political Realities. *Land*, 9(5), pp.156-174.

Stringer, L.C., Dougill, A.J., Thomas, A.D., Spracklen, D.V., Chesterman, S., Speranza, C.I., Rueff, H., Riddell, M., Williams, M., Beedy, T. and Abson, D.J., **2012**. Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands. *Environmental Science & Policy*, 19, pp.121-135.

Strohmeier, S., Fukai, S., Haddad, M., AlNsour, M., Mudabber, M., Akimoto, K., Yamamoto, S., Evett, S. and Oweis, T., **2021**. Rehabilitation of degraded rangelands in Jordan: The effects of mechanized micro water harvesting on hill-slope scale soil water and vegetation dynamics. *Journal of Arid Environments*, 185, pp.104338-104349.

Taimeh, A., **2003**. Strategy for Badia Development. *A paper presented at the workshop on selection of Benchmark Sites Badia, NCARE, Jordan.*, pp.6-12.

Tarawneh, Q. and Kadıoğlu, M., **2003**. An analysis of precipitation climatology in Jordan. *Theoretical and Applied Climatology*, 74(1-2), pp.123-136.

Thamo, T., Pannell, D.J., Kragt, M.E., Robertson, M.J. and Polyakov, M., **2017**. Dynamics and the economics of carbon sequestration: common oversights and their implications. *Mitigation and Adaptation Strategies for Global Change*, 22(7), pp.1095-1111.

Vallerani System., **2013**. Accessed at: www.vallerani.com/wp/ [5/10/20]

Van Groenigen, J.W., Van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S. and Van Groenigen, K.J., **2017**. Sequestering soil organic carbon: a nitrogen dilemma. *Environmental Science and Technology*, 51, pp. 4738-4739.

Vanguelova, E.I., Bonifacio, E., De Vos, B., Hoosbeek, M.R., Berger, T.W., Vesterdal, L., Armolaitis, K., Celi, L., Dinca, L., Kjønaas, O.J. and Pavlenda, P., **2016**. Sources of errors and uncertainties in the assessment of forest soil carbon stocks at different scales—review and recommendations. *Environmental Monitoring and Assessment*, 188(11), pp.1-24.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F. and Masui, T., **2011**. The representative concentration pathways: an overview. *Climatic change*, 109(1-2), pp.5-32.

Verbist, J., **2020**. The suitability of the Vallerani system: a case study of the Jordan Badia (BSc Thesis), Wageningen University and Research Centre: Wageningen, Netherlands.

Veron, S.R., Paruelo, J.M. and Oesterheld, M., **2006**. Assessing desertification. *Journal of Arid Environments*, 66(4), pp.751-763.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. and Dokken, D.J., **2000**. *IPCC special report on land use, land-use change, and forestry*.

Wiedmann, T., Lenzen, M., Keyßer, L.T. and Steinberger, J.K., **2020**. Scientists' warning on affluence. *Nature Communications*, 11(1), pp.1-10.

Wiesmeier, M., Hübner, R., Spörlein, P., Geuß, U., Hangen, E., Reischl, A., Schilling, B., von Lützow, M. and Kögel-Knabner, I., **2014**. Carbon sequestration potential of soils in southeast Germany derived from stable soil organic carbon saturation. *Global Change Biology*, 20(2), pp.653-665.

Williams, J.R., Peterson, J.M. and Mooney, S., **2005**. The value of carbon credits: Is there a final answer?. *Journal of soil and Water Conservation*, 60(2), pp.36A-40A.

Yadav, S.S. and Lal, R., **2018**. Vulnerability of women to climate change in arid and semi-arid regions: The case of India and South Asia. *Journal of Arid Environments,* 149, pp.4-17.

Yokozawa, M., Shirato, Y., Sakamoto, T., Yonemura, S., Nakai, M. and Ohkura, T., **2010**. Use of the RothC model to estimate the carbon sequestration potential of organic matter application in Japanese arable soils. *Soil Science & Plant Nutrition*, 56(1), pp.168-176.

Young, R.R., Wilson, B., Harden, S. and Bernardi, A., **2009**. Accumulation of soil carbon under zero tillage cropping and perennial vegetation on the Liverpool Plains, eastern Australia. *Soil Research*, 47(3), pp.273-285.

Zeidan., A. **2020**., Middle East. Britannica. Accessed at: https://www.britannica.com/place/Middle-East [6/10/20]

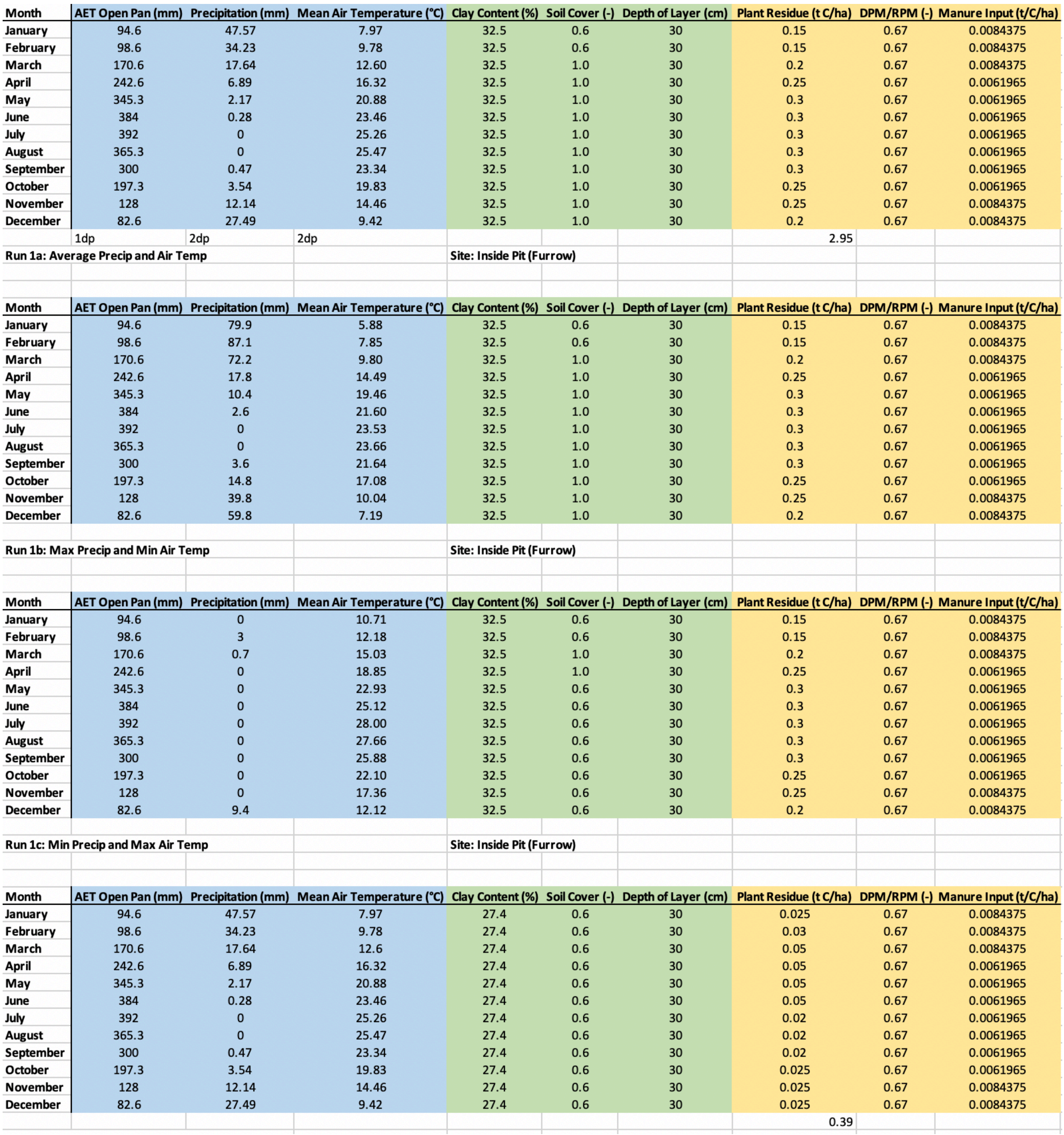
Zimmermann, M., Leifeld, J., Schmidt, M.W.I., Smith, P. and Fuhrer, J., **2007**. Measured soil organic matter fractions can be related to pools in the RothC model. *European Journal of Soil Science*, 58(3), pp.658-667.

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

Appendix 1: List of Variables

Variable	Name	Units
a	Temperature rate modifying factor	[-]
b	Topsoil moisture rate modifying factor	[-]
c	Land cover factor	[-]
d	Soil depth	[cm]
e	Soil stone content	[%]
f	Average annual precipitation	[mm]
k	Decomposition rate constant	[yr^{-1}]
l	Soil clay content	[%]
n	Soil sand content	[%]
p	Rate of change for carbon price	[%/year]
r	Market discount in carbon price	[$/ton]
s	Slope	[°]
T	Temperature	[°C]
t	Time	[months]
V	Price of carbon	[$/ton]

Appendix 2: Model Run Detail



Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	94.6	47.57	7.97	32.5	0.6	30	0.15	0.67	0.0084375
February	98.6	34.23	9.78	32.5	0.6	30	0.15	0.67	0.0084375
March	170.6	17.64	12.60	32.5	1.0	30	0.2	0.67	0.0084375
April	242.6	6.89	16.32	32.5	1.0	30	0.25	0.67	0.0061965
May	345.3	2.17	20.88	32.5	1.0	30	0.3	0.67	0.0061965
June	384	0.28	23.46	32.5	1.0	30	0.3	0.67	0.0061965
July	392	0	25.26	32.5	1.0	30	0.3	0.67	0.0061965
August	365.3	0	25.47	32.5	1.0	30	0.3	0.67	0.0061965
September	300	0.47	23.34	32.5	1.0	30	0.3	0.67	0.0061965
October	197.3	3.54	19.83	32.5	1.0	30	0.25	0.67	0.0061965
November	128	12.14	14.46	32.5	1.0	30	0.25	0.67	0.0084375
December	82.6	27.49	9.42	32.5	1.0	30	0.2	0.67	0.0084375
	1dp	2dp	2dp				2.95		

Run 1a: Average Precip and Air Temp **Site: Inside Pit (Furrow)**

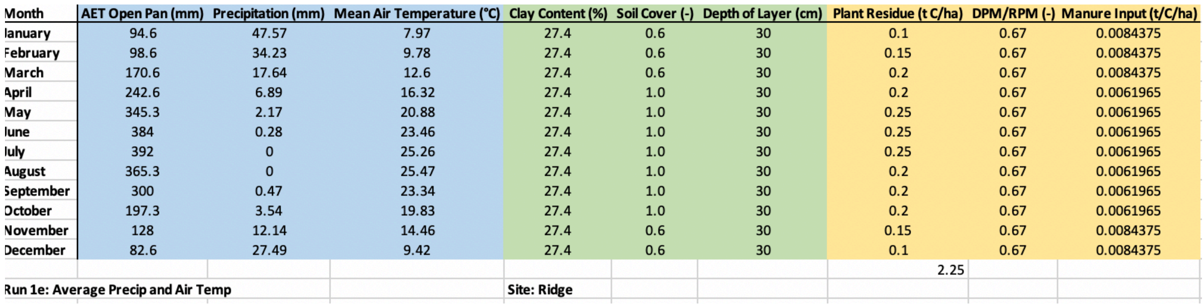
Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	94.6	79.9	5.88	32.5	0.6	30	0.15	0.67	0.0084375
February	98.6	87.1	7.85	32.5	0.6	30	0.15	0.67	0.0084375
March	170.6	72.2	9.80	32.5	1.0	30	0.2	0.67	0.0084375
April	242.6	17.8	14.49	32.5	1.0	30	0.25	0.67	0.0061965
May	345.3	10.4	19.46	32.5	1.0	30	0.3	0.67	0.0061965
June	384	2.6	21.60	32.5	1.0	30	0.3	0.67	0.0061965
July	392	0	23.53	32.5	1.0	30	0.3	0.67	0.0061965
August	365.3	0	23.66	32.5	1.0	30	0.3	0.67	0.0061965
September	300	3.6	21.64	32.5	1.0	30	0.3	0.67	0.0061965
October	197.3	14.8	17.08	32.5	1.0	30	0.25	0.67	0.0061965
November	128	39.8	10.04	32.5	1.0	30	0.25	0.67	0.0084375
December	82.6	59.8	7.19	32.5	1.0	30	0.2	0.67	0.0084375

Run 1b: Max Precip and Min Air Temp **Site: Inside Pit (Furrow)**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	94.6	0	10.71	32.5	0.6	30	0.15	0.67	0.0084375
February	98.6	3	12.18	32.5	0.6	30	0.15	0.67	0.0084375
March	170.6	0.7	15.03	32.5	1.0	30	0.2	0.67	0.0084375
April	242.6	0	18.85	32.5	1.0	30	0.25	0.67	0.0061965
May	345.3	0	22.93	32.5	0.6	30	0.3	0.67	0.0061965
June	384	0	25.12	32.5	0.6	30	0.3	0.67	0.0061965
July	392	0	28.00	32.5	0.6	30	0.3	0.67	0.0061965
August	365.3	0	27.66	32.5	0.6	30	0.3	0.67	0.0061965
September	300	0	25.88	32.5	0.6	30	0.3	0.67	0.0061965
October	197.3	0	22.10	32.5	0.6	30	0.25	0.67	0.0061965
November	128	0	17.36	32.5	0.6	30	0.25	0.67	0.0084375
December	82.6	9.4	12.12	32.5	0.6	30	0.2	0.67	0.0084375

Run 1c: Min Precip and Max Air Temp **Site: Inside Pit (Furrow)**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	94.6	47.57	7.97	27.4	0.6	30	0.025	0.67	0.0084375
February	98.6	34.23	9.78	27.4	0.6	30	0.03	0.67	0.0084375
March	170.6	17.64	12.6	27.4	0.6	30	0.05	0.67	0.0084375
April	242.6	6.89	16.32	27.4	0.6	30	0.05	0.67	0.0061965
May	345.3	2.17	20.88	27.4	0.6	30	0.05	0.67	0.0061965
June	384	0.28	23.46	27.4	0.6	30	0.05	0.67	0.0061965
July	392	0	25.26	27.4	0.6	30	0.02	0.67	0.0061965
August	365.3	0	25.47	27.4	0.6	30	0.02	0.67	0.0061965
September	300	0.47	23.34	27.4	0.6	30	0.02	0.67	0.0061965
October	197.3	3.54	19.83	27.4	0.6	30	0.025	0.67	0.0061965
November	128	12.14	14.46	27.4	0.6	30	0.025	0.67	0.0084375
December	82.6	27.49	9.42	27.4	0.6	30	0.025	0.67	0.0084375
							0.39		



Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
Ianuary	94.6	47.57	7.97	27.4	0.6	30	0.1	0.67	0.0084375
February	98.6	34.23	9.78	27.4	0.6	30	0.15	0.67	0.0084375
March	170.6	17.64	12.6	27.4	0.6	30	0.2	0.67	0.0084375
April	242.6	6.89	16.32	27.4	1.0	30	0.2	0.67	0.0061965
May	345.3	2.17	20.88	27.4	1.0	30	0.25	0.67	0.0061965
Iune	384	0.28	23.46	27.4	1.0	30	0.25	0.67	0.0061965
Iuly	392	0	25.26	27.4	1.0	30	0.25	0.67	0.0061965
August	365.3	0	25.47	27.4	1.0	30	0.2	0.67	0.0061965
September	300	0.47	23.34	27.4	1.0	30	0.2	0.67	0.0061965
Dctober	197.3	3.54	19.83	27.4	1.0	30	0.2	0.67	0.0061965
November	128	12.14	14.46	27.4	0.6	30	0.15	0.67	0.0084375
December	82.6	27.49	9.42	27.4	0.6	30	0.1	0.67	0.0084375
							2.25		

Run 1e: Average Precip and Air Temp **Site: Ridge**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	0.6	30	0.15	0.67	0	
February	98.6	34.23	9.78	32.5	0.6	30	0.15	0.67	0	
March	170.6	17.64	12.60	32.5	1.0	30	0.2	0.67	0	
April	242.6	6.89	16.32	32.5	1.0	30	0.25	0.67	0	Dry Season
May	345.3	2.17	20.88	32.5	1.0	30	0.3	0.67	0	Dry Season
June	384	0.28	23.46	32.5	1.0	30	0.3	0.67	0	Dry Season
July	392	0.00	25.26	32.5	1.0	30	0.3	0.67	0	Dry Season
August	365.3	0.00	25.47	32.5	1.0	30	0.3	0.67	0	Dry Season
September	300	0.47	23.34	32.5	1.0	30	0.3	0.67	0	Dry Season
October	197.3	3.54	19.83	32.5	1.0	30	0.25	0.67	0	Dry Season
November	128	12.14	14.46	32.5	1.0	30	0.25	0.67	0	
December	82.6	27.49	9.42	32.5	1.0	30	0.2	0.67	0	

Run2a: Assuming no manure input **Site: Inside Pit (Furrow)**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	0.6	30	0.15	0.67	0.0084375	
February	98.6	34.23	9.78	32.5	0.6	30	0.15	0.67	0.0084375	
March	170.6	17.64	12.60	32.5	1.0	30	0.2	0.67	0.0084375	
April	242.6	6.89	16.32	32.5	1.0	30	0.25	0.67	0.0061965	Dry Season
May	345.3	2.17	20.88	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
June	384	0.28	23.46	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
July	392	0.00	25.26	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
August	365.3	0.00	25.47	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
September	300	0.47	23.34	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
October	197.3	3.54	19.83	32.5	1.0	30	0.25	0.67	0.0061965	Dry Season
November	128	12.14	14.46	32.5	1.0	30	0.25	0.67	0.0084375	
December	82.6	27.49	9.42	32.5	1.0	30	0.2	0.67	0.0084375	

Run2b: Average manure input **Site: Inside Pit (Furrow)**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	0.6	30	0.15	0.67	0.01	
February	98.6	34.23	9.78	32.5	0.6	30	0.15	0.67	0.01	
March	170.6	17.64	12.60	32.5	1.0	30	0.2	0.67	0.01	
April	242.6	6.89	16.32	32.5	1.0	30	0.25	0.67	0.008	Dry Season
May	345.3	2.17	20.88	32.5	1.0	30	0.3	0.67	0.008	Dry Season
June	384	0.28	23.46	32.5	1.0	30	0.3	0.67	0.008	Dry Season
July	392	0.00	25.26	32.5	1.0	30	0.3	0.67	0.008	Dry Season
August	365.3	0.00	25.47	32.5	1.0	30	0.3	0.67	0.008	Dry Season
September	300	0.47	23.34	32.5	1.0	30	0.3	0.67	0.008	Dry Season
October	197.3	3.54	19.83	32.5	1.0	30	0.25	0.67	0.008	Dry Season
November	128	12.14	14.46	32.5	1.0	30	0.25	0.67	0.01	
December	82.6	27.49	9.42	32.5	1.0	30	0.2	0.67	0.01	

Run2c: Max manure input **Site: Inside Pit (Furrow)**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	1.0	30	0.025	0.67	0.0084375	
February	98.6	34.23	9.78	32.5	1.0	30	0.03	0.67	0.0084375	
March	170.6	17.64	12.60	32.5	1.0	30	0.05	0.67	0.0084375	
April	242.6	6.89	16.32	32.5	1.0	30	0.05	0.67	0.0061965	Dry Season
May	345.3	2.17	20.88	32.5	0.6	30	0.05	0.67	0.0061965	Dry Season
June	384	0.28	23.46	32.5	0.6	30	0.05	0.67	0.0061965	Dry Season
July	392	0.00	25.26	32.5	0.6	30	0.02	0.67	0.0061965	Dry Season
August	365.3	0.00	25.47	32.5	0.6	30	0.02	0.67	0.0061965	Dry Season
September	300	0.47	23.34	32.5	0.6	30	0.02	0.67	0.0061965	Dry Season
October	197.3	3.54	19.83	32.5	0.6	30	0.025	0.67	0.0061965	Dry Season
November	128	12.14	14.46	32.5	0.6	30	0.025	0.67	0.0084375	
December	82.6	27.49	9.42	32.5	0.6	30	0.025	0.67	0.0084375	

Run2d: Average manure input **Site: Interspace**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	1.0	30	0.1	0.67	0.0084375	
February	98.6	34.23	9.78	32.5	1.0	30	0.15	0.67	0.0084375	
March	170.6	17.64	12.60	32.5	1.0	30	0.2	0.67	0.0084375	
April	242.6	6.89	16.32	32.5	1.0	30	0.2	0.67	0.0061965	Dry Season
May	345.3	2.17	20.88	32.5	0.6	30	0.25	0.67	0.0061965	Dry Season
June	384	0.28	23.46	32.5	0.6	30	0.25	0.67	0.0061965	Dry Season
July	392	0.00	25.26	32.5	0.6	30	0.25	0.67	0.0061965	Dry Season
August	365.3	0.00	25.47	32.5	0.6	30	0.2	0.67	0.0061965	Dry Season
September	300	0.47	23.34	32.5	0.6	30	0.2	0.67	0.0061965	Dry Season
October	197.3	3.54	19.83	32.5	0.6	30	0.2	0.67	0.0061965	Dry Season
November	128	12.14	14.46	32.5	1.0	30	0.15	0.67	0.0084375	
December	82.6	27.49	9.42	32.5	1.0	30	0.1	0.67	0.0084375	

Run2e: Average manure input **Site: Ridge**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	0.6	30	0.15	0.67	0.0084375	
February	98.6	34.23	9.78	32.5	0.6	30	0.15	0.67	0.0084375	
March	170.6	17.64	12.60	32.5	1.0	30	0.2	0.67	0.0084375	
April	242.6	6.89	16.32	32.5	1.0	30	0.25	0.67	0.0061965	Dry Season
May	345.3	2.17	20.88	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
June	384	0.28	23.46	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
July	392	0.00	25.26	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
August	365.3	0.00	25.47	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
September	300	0.47	23.34	32.5	1.0	30	0.3	0.67	0.0061965	Dry Season
October	197.3	3.54	19.83	32.5	1.0	30	0.25	0.67	0.0061965	Dry Season
November	128	12.14	14.46	32.5	1.0	30	0.25	0.67	0.0084375	
December	82.6	27.49	9.42	32.5	1.0	30	0.2	0.67	0.0084375	
							2.95			

Run2f: 70/30 above/below ground biomass **Site: Inside Pit (Furrow)**

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)	
January	94.6	47.57	7.97	32.5	0.6	30	0.105	0.67	0.0084375	
February	98.6	34.23	9.78	32.5	0.6	30	0.105	0.67	0.0084375	
March	170.6	17.64	12.60	32.5	1.0	30	0.14	0.67	0.0084375	
April	242.6	6.89	16.32	32.5	1.0	30	0.175	0.67	0.0061965	Dry Season
May	345.3	2.17	20.88	32.5	1.0	30	0.21	0.67	0.0061965	Dry Season
June	384	0.28	23.46	32.5	1.0	30	0.21	0.67	0.0061965	Dry Season
July	392	0.00	25.26	32.5	1.0	30	0.21	0.67	0.0061965	Dry Season
August	365.3	0.00	25.47	32.5	1.0	30	0.21	0.67	0.0061965	Dry Season
September	300	0.47	23.34	32.5	1.0	30	0.21	0.67	0.0061965	Dry Season
October	197.3	3.54	19.83	32.5	1.0	30	0.175	0.67	0.0061965	Dry Season
November	128	12.14	14.46	32.5	1.0	30	0.175	0.67	0.0084375	
December	82.6	27.49	9.42	32.5	1.0	30	0.14	0.67	0.0084375	
							2.065			

Run2g: 75/25 above/below ground biomass

Site Inside Pit (Furrow)

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	94.6	47.57	7.97	32.5	0.6	30	0.195	0.67	0.0084375
February	98.6	34.23	9.78	32.5	0.6	30	0.195	0.67	0.0084375
March	170.6	17.64	12.60	32.5	1.0	30	0.26	0.67	0.0084375
April	242.6	6.89	16.32	32.5	1.0	30	0.325	0.67	0.0061965
May	345.3	2.17	20.88	32.5	1.0	30	0.39	0.67	0.0061965
June	384	0.28	23.46	32.5	1.0	30	0.39	0.67	0.0061965
July	392	0.00	25.26	32.5	1.0	30	0.39	0.67	0.0061965
August	365.3	0.00	25.47	32.5	1.0	30	0.39	0.67	0.0061965
September	300	0.47	23.34	32.5	1.0	30	0.39	0.67	0.0061965
October	197.3	3.54	19.83	32.5	1.0	30	0.325	0.67	0.0061965
November	128	12.14	14.46	32.5	1.0	30	0.325	0.67	0.0084375
December	82.6	27.49	9.42	32.5	1.0	30	0.26	0.67	0.0084375
							3.835		

Run 2h 65/35 above/below ground biomass

Site: Inside Pit (Furrow)

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	100.3	42.81	9.97	32.5	1.0	30	0.15	0.67	0.0084375
February	104.5	30.81	11.78	32.5	1.0	30	0.15	0.67	0.0084375
March	180.8	15.88	14.6	32.5	1.0	30	0.2	0.67	0.0084375
April	257.2	6.20	18.32	32.5	1.0	30	0.25	0.67	0.0061965
May	366.0	1.95	22.88	32.5	0.6	30	0.3	0.67	0.0061965
June	407.0	0.25	25.46	32.5	0.6	30	0.3	0.67	0.0061965
July	415.5	0.00	27.26	32.5	0.6	30	0.3	0.67	0.0061965
August	387.2	0.00	27.47	32.5	0.6	30	0.3	0.67	0.0061965
September	318.0	0.42	25.34	32.5	0.6	30	0.3	0.67	0.0061965
October	209.1	3.19	21.83	32.5	0.6	30	0.25	0.67	0.0061965
November	135.7	10.93	16.46	32.5	0.6	30	0.25	0.67	0.0084375
December	87.6	24.74	11.42	32.5	0.6	30	0.2	0.67	0.0084375

Run4a: RCP 2.6 Climate Scenario

Site: Furrow

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	102.2	40.91	11.17	32.5	1	30	0.15	0.67	0.0084375
February	106.5	29.44	12.98	32.5	1	30	0.15	0.67	0.0084375
March	184.2	15.17	15.8	32.5	1	30	0.2	0.67	0.0084375
April	262.0	5.93	19.52	32.5	1	30	0.25	0.67	0.0061965
May	372.9	1.87	24.08	32.5	0.6	30	0.3	0.67	0.0061965
June	414.7	0.24	26.66	32.5	0.6	30	0.3	0.67	0.0061965
July	423.4	0.00	28.46	32.5	0.6	30	0.3	0.67	0.0061965
August	394.5	0.00	28.67	32.5	0.6	30	0.3	0.67	0.0061965
September	324.0	0.40	26.54	32.5	0.6	30	0.3	0.67	0.0061965
October	213.1	3.04	23.03	32.5	0.6	30	0.25	0.67	0.0061965
November	138.2	10.44	17.66	32.5	0.6	30	0.25	0.67	0.0084375
December	89.2	23.64	12.62	32.5	0.6	30	0.2	0.67	0.0084375

Run4b: RCP 4.5 Climate Scenario

Site: Furrow

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	103.1	39.48	11.47	32.5	1	30	0.15	0.67	0.0084375
February	107.5	28.41	13.28	32.5	1	30	0.15	0.67	0.0084375
March	186.0	14.64	16.1	32.5	1	30	0.2	0.67	0.0084375
April	264.4	5.72	19.82	32.5	1	30	0.25	0.67	0.0061965
May	376.4	1.80	24.38	32.5	0.6	30	0.3	0.67	0.0061965
June	418.6	0.23	26.96	32.5	0.6	30	0.3	0.67	0.0061965
July	427.3	0.00	28.76	32.5	0.6	30	0.3	0.67	0.0061965
August	398.2	0.00	28.97	32.5	0.6	30	0.3	0.67	0.0061965
September	327.0	0.39	26.84	32.5	0.6	30	0.3	0.67	0.0061965
October	215.1	2.94	23.33	32.5	0.6	30	0.25	0.67	0.0061965
November	139.5	10.08	17.96	32.5	0.6	30	0.25	0.67	0.0084375
December	90.0	22.82	12.92	32.5	0.6	30	0.2	0.67	0.0084375

Run4c: RCP 6 Climate Scenario

Site: Furrow

Month	AET Open Pan (mm)	Precipitation (mm)	Mean Air Temperature (°C)	Clay Content (%)	Soil Cover (-)	Depth of Layer (cm)	Plant Residue (t C/ha)	DPM/RPM (-)	Manure Input (t/C/ha)
January	105.0	38.06	13.67	32.5	1	30	0.15	0.67	0.0084375
February	109.4	27.38	15.48	32.5	1	30	0.15	0.67	0.0084375
March	189.4	14.11	18.3	32.5	1	30	0.2	0.67	0.0084375
April	269.3	5.51	22.02	32.5	1	30	0.25	0.67	0.0061965
May	383.3	1.74	26.58	32.5	0.6	30	0.3	0.67	0.0061965
June	426.2	0.22	29.16	32.5	0.6	30	0.3	0.67	0.0061965
July	435.1	0.00	30.96	32.5	0.6	30	0.3	0.67	0.0061965
August	405.5	0.00	31.17	32.5	0.6	30	0.3	0.67	0.0061965
September	333.0	0.38	29.04	32.5	0.6	30	0.3	0.67	0.0061965
October	219.0	2.83	25.53	32.5	0.6	30	0.25	0.67	0.0061965
November	142.1	9.71	20.16	32.5	0.6	30	0.25	0.67	0.0084375
December	91.7	21.99	15.12	32.5	0.6	30	0.2	0.67	0.0084375

Run4d: RCP 8.5 Climate Scenario

Site: Furrow