JNCC Report
No: 634

A Natural Capital Approach to Landscape Planning: a Pilot Project in Colchagua Valley, Chile

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September 2019

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ISSN 0963-8091

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This report should be cited as:

Barbosa, O., Colson, D., Duran, P., Godoy, K., Jones, A., Jones, G., Harris, M., Harrison, S., Tierney, M., Trippier, B., Smith, M. & Wright, E. (2019) A Natural Capital Approach to Landscape Planning: a Pilot Project in Colchagua Valley, Chile. *JNCC Report No. 634*, JNCC, Peterborough, ISSN 0963-8091.

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http://jncc.gov.uk/default.aspx?page=6675.

Acknowledgement:

JNCC would like to thank all of the vineyards participating in the Wine, Climate Change and Biodiversity Programme and Alastair Graham of Geoger Ltd. for their contributions to the project.

This project was funded by the United Kingdom's Department for the Environment, Farming and Rural Affairs (DEFRA).

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1 Natural Capital Approach to Landscape Planning: a Pilot Project in Colchagua Valley

Through the South Atlantic Research Outreach Programme, the Joint Nature Conservation Committee (UK) has collaborated with The Wine, Climate Change and Biodiversity Program (Programa Vino, Cambio Climático y Biodiversidad [VCCB]) which is a scientific initiative of the Institute of Ecology and Biodiversity and the University Austral of Chile. The initiative works to show that biodiversity conservation and the development of the Chilean wine industry are compatible endeavours. VCCB works closely with 17 vineyards in the Colchagua Valley, central Chile.

The *Natural Capital Approach to Landscape Planning: a Pilot Project in Colchagua Valley*, builds upon long standing work undertaken by VCCB and partner vineyards since 2008 (VCCB 2008). The project draws upon the natural capital work that JNCC has undertaken with the UK Overseas Territories in the South Atlantic region (JNCC 2019). The project combines industry knowledge with ecosystem sciences and looks to disentangle and quantify the interactions between land management, biotic and abiotic factors, and the effects on ecosystem services relevant to wine producing businesses.

In 2017, Chile exported 9% of its wine to the United Kingdom, with a value of US$203 million. Projects such as this are critical to the UK and its trading partners in understanding how emerging science and technology can be translated for use by businesses and underpin sustainable supply chains that deliver long-term value, whilst protecting the ecosystems that support the global economy.

The project is funded by the United Kingdom's Department for the Environment, Farming and Rural Affairs (DEFRA).

1.1 Project Objectives

The high-level project objectives are:

- Demonstrate how Earth Observation data, ecosystem modelling and local ecological knowledge can be combined to inform ecosystem-based management.
- Work with the wine industry to identify where the application of mapping and modelling outputs can offer commercial benefits through sustainable supply chains.
- Strengthen future collaboration between the United Kingdom and Partners in the South Atlantic region.

2 Introduction

The Colchagua Valley is part of Chile's Mediterranean biome that can be found between the regions of Coquimbo (29°02') and Bío-Bío (38°30'). It plays an important role in the productivity of Chile's agriculture and viticulture. The biome is considered a priority for biological conservation as it represents 16% of the continental surface of Chile, yet hosts 50% of Chilean flora and more than half of the country's endemic species (Barbosa & Godoy 2014).

Like many of the world's ecosystems, the Chilean Mediterranean biome is affected by land conversion to agriculture and urban development. The wineries, who are the stakeholders in this project, have been working with VCCB since 2008, exploring ways in which their businesses can sustainably manage their land to conserve habitats in both their vineyards and the surrounding areas, enhancing the local biodiversity.

The project goes to demonstrate how ecosystem mapping and modelling can be established in-line with user requirements and provide tools that help bring environmental data into decision making processes.

Evidence-based environmental management is critical for avoiding supply chain disruption and potential infrastructure damage, such as identifying fire risks and implementing avoidance strategies. Better understanding of catchment processes can lead to informed land management planning and predicting factors such as water stress and pollution risk that are vital to the future sustainability of any business.

2.1 The Ecosystem Approach and Viticulture

An ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation, sustainability and equitable use, recognising that humans, with their cultural diversity, are an integral element of many ecosystems (UNEP 2016).

Integrating nature (biodiversity) and ecosystem services into management strategies can help businesses recognise their impacts and dependencies on the natural environment. This can help them adapt to potential adverse effects brought about by environmental change, such as climate change, by maintaining and increasing the resilience of the ecosystems that their businesses rely upon (CBD 2018).

2.1.1 Ecosystem System Services Important to Viticulture

Ecosystem services are the direct and indirect benefits that humanity obtains from nature. These benefits vary from one system to another; many are essential for the existence of humanity. The Common International Classification of Ecosystem Services (CICES 2018) defines these services as:

Provisioning	Production of freshwater, oxygen, timber, food, bio-based energy.
Regulation & Maintenance	Control of erosion and purification of water, climate regulation, flood mitigation, nutrient cycle and decomposition of organic material, soil formation, pollination and the provision of habitats for biodiversity.
Cultural	Recreation, aesthetic and emblematic values of species or landscapes, and spiritual, intellectual and other human interactions with ecosystems.

Through a series of discussions and workshops, stakeholders identified the following ecosystem services as most relevant to wine production:

- Natural biocontrol of pest species
- Biodiversity
- Aesthetic appeal
- Prevention of fire spread
- Reduction in topsoil loss

- Avoidance of natural nutrient enrichment
- Water supply and water quality regulation

3 Area of Interest – Colchagua Valley

The Colchagua Valley is located in central Chile in the General Liberatador Bernardo O' Higgins region, 130 km southwest of the capital Santiago. The valley itself is approximately 120 km long and 35 km wide and it is estimated that vineyards cover around 200 km² of the valley's land area. The area of interest for the project covers approximately 6,900 km².

The valley is carved by the Tinguiririca River flowing from the headwaters in the glaciated Andean Mountains to the east, down to the lowland grasslands towards the Pacific coast in the west. As a result, the valley experiences a Mediterranean climate bordered by mountain ranges, with glacial melt being an important water source throughout the year (Bravo *et al*. 2017).

Wine makes up 3.9% of Chile's export market, worth $US2.2 Bn in 2017 (Simoes & Hidalgo 2011). The Colchagua valley in particular is famed for its winegrowing, with production dating back to 1542. In 2012, sales of Colchagua wines generated US$331.5 million (Viñas de Colchagua 2012).

Figure 1. Shows the location of the Colchagua Valley area of interest.

4 Mapping the Colchagua Valley

Habitat maps are key to understanding the distribution and extent of different land uses across the landscape and in assessing how the environment responds to changing land management. They are an essential requirement for further analysis through natural capital accounting, ecosystem service mapping, the creation of tools to facilitate better management practice, interpreting and targeting biodiversity monitoring and delivering policies. There are many global land cover and land use products available, but these are often low resolution data which do not provide enough detail to perform analyses on a regional level. Therefore, an updated habitat map was necessary in order to carry out the ecosystem service mapping and modelling.

European Space Agency Copernicus datasets have been identified as a key data source for this project, because of their open access and spatial resolution of 10 metres. For the mapping work, both Sentinel-1[1], a radar mission, and Sentinel-2[2], an optical mission, were used to capture as many features in the landscape as possible. In comparison with other open access Earth Observation datasets, Sentinel-2 covers the globe more frequently than other observing systems, and is an operational mission as opposed to research based. The Sentinel-2 mission also endeavours to continue to provide open datasets for the future, with a further two satellites planned for launch to join the existing constellation.

Following the completion of the first draft habitat map ground data were collected and used to validate and analyse the accuracy of the modelled outputs, providing an indication of how many land cover classes are identified correctly. Overall, accuracy of the habitat map created by the project is 78%. Further information on the habitat mapping process are contained in Section 1 and Appendix 1 of the accompanying technical report. The habitat map and accompanying data were provided to project partners for future use.

[1] Sentinel-1A and Sentinel-1B carry a C-band synthetic-aperture radar instrument which collection data in all-weather, day or night. It has spatial resolution of down to 5m and a swath of up to 400 km. Synthetic-aperture radar (SAR) is a form of radar used to two-dimensional images or three-dimensional reconstructions of objects, such as landscapes.

[2] Sentinel-2 is an optical constellation of satellites, imagery is limited by cloud cover. To secure cloud-free data investigation is required to identify suitable cloud free images. Seasonal changes and differences can be detected as these can be critical to habitat and land use identification. For example, leaf flushes and snow cover vary between seasons.

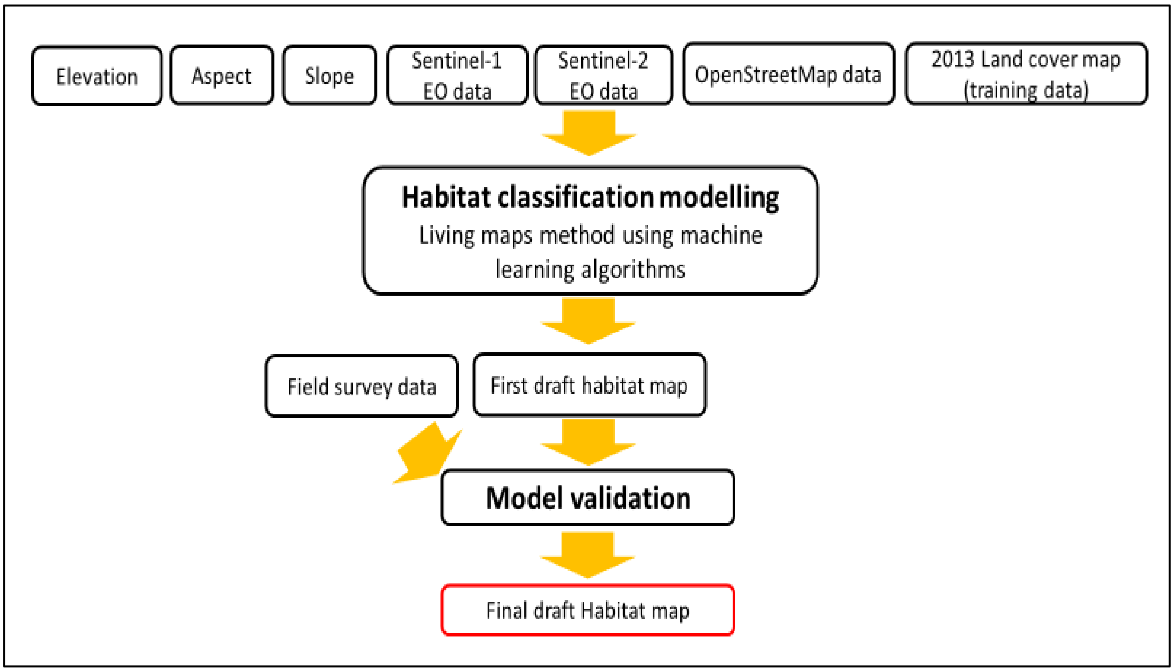

Figure 2. Representation of the mapping process undertaken to create the habitat map.

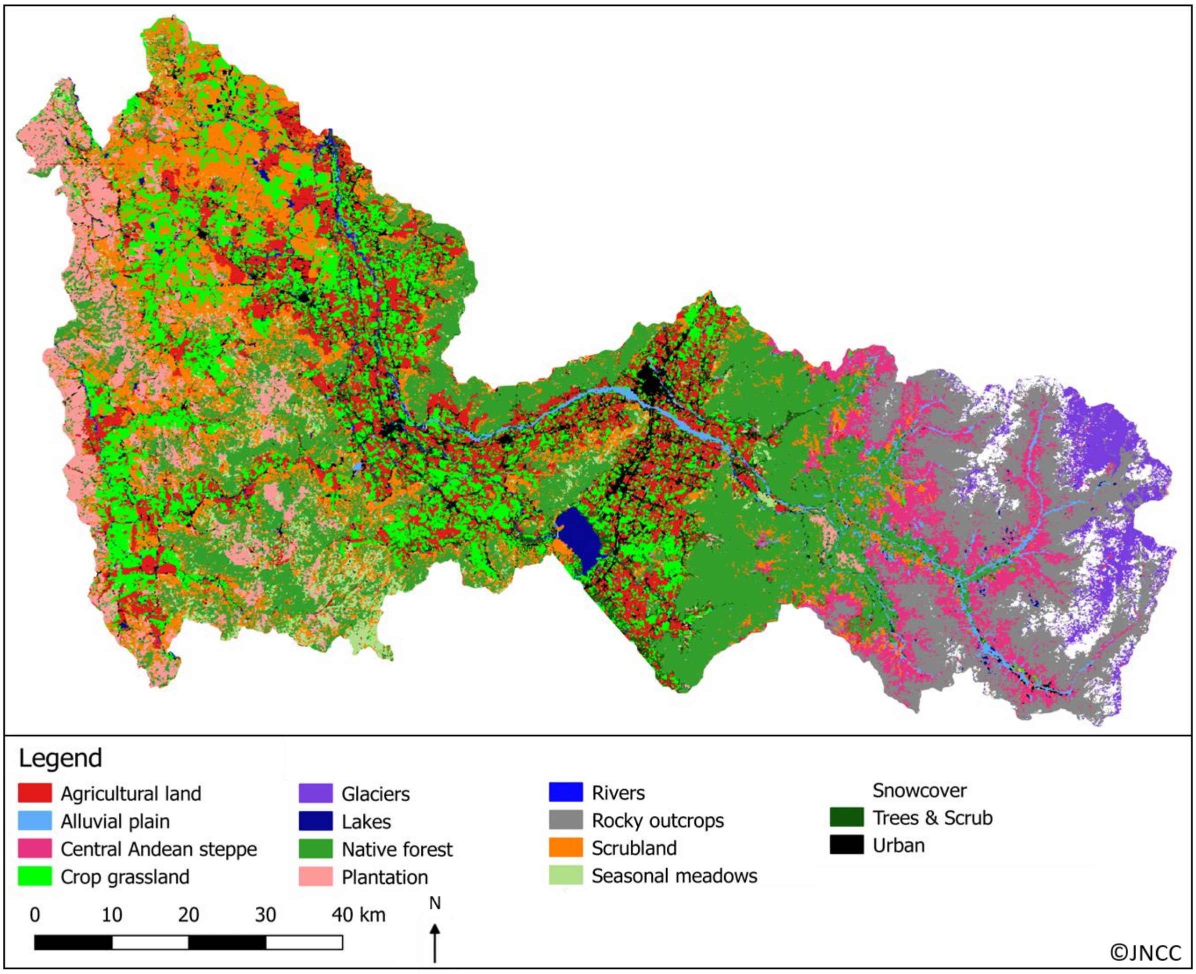

Figure 3. Shows a representation of the habitat map output. Table 1 below provides a definition of what is contained within the different classes.

Table 1. Class names and descriptions.

Class Name	**Class Description**
Agricultural land	All areas used as vineyards and for fruit production.
Alluvial plain	A landform created by deposition of material eroded higher up the catchment.
Central Andean Steppe	Montane grassland and shrublands ecoregion in the high elevations of the southern Andes mountain range.
Crop grassland	All areas used to grow crop such as maize on a rotational basis (i.e. not permanent crop types), and areas used for grazing.
Glaciers	A slowly moving mass or river of ice formed by the accumulation and compaction of snow on mountains or near the poles.
Lakes	Areas of water bodies, including naturally formed lakes and reservoirs.
Native forest	A forest composed of indigenous trees and not classified as forest plantation.
Plantation forest	A forest established by planting and/or seeding in the process of afforestation or reforestation. It consists of introduced species in most cases.
Rivers	A river channel that includes a permanent flow of water.
Rocky outcrops	An area of bedrock that is exposed. Covers varying types of rock.
Scrubland	An area of land consisting of scrub vegetation.
Seasonal meadows	An area consisting of grassland that appears on a seasonal basis.
Snow cover	An area that is permanently covered in snow.
Trees & Scrub	Areas of trees, woodland and scrub that occur on the fringes of field boundaries, river banks and in urban areas.
Urban	Built infrastructure, including houses, farm buildings, roads and any other built structures, tarmac, concrete or gravel.

5 Biodiversity supporting ecosystem service

Biodiversity within vineyards has been explored in a number of studies and has shown to increase with increasing proximity to nearby semi-natural habitat, as opposed to highly disturbed land such as urban or agricultural land (Grashof-Bokdam & van Langevelde 2005; Márquez-García *et al*. 2018). High-quality wines are associated with the concept of 'terroir', which encompasses regional characteristics of the vineyard such as climate, grape variety, soil and the interactions that occur with indigenous microorganisms, all factors contributing to the quality of the wine. Natural habitats can be potential reservoirs of microorganisms and can safeguard the identity of terroir over time (Castañeda *et al*. 2018; Jara *et al*. 2016).

Biodiversity is key with regard to encouraging the natural yeasts and fungal species diversity as part of the 'terroir' characteristic. Fungal diversity and maintaining a correct balance of yeast species within the environment is important to the flavour and quality of the wine produced and has been linked to plant diversity and the distance of the vines to the surrounding semi-natural habitat (Castañeda *et al*. 2018).

Pest species are key concerns for vineyards. VCCB's stakeholders identified rabbits, red spider mite (*Brevipalpus chilensis),* mildew ('Oiddio') and vine wood fungi as particular pest species in the region. Guidance from VCCB (Barbosa & Godoy 2014) highlights how creating ecological corridors by using buffer strips and cover crops can help reduce pest pressures by encouraging natural predators, whereas monoculture vineyard fields are more susceptible to pests and disease.

Cattle management is also seen to aid in pest prevention, in addition to fire prevention; as shorter grasses are maintained reducing pest refugia, ignition potential and fuel availability (Journet 2016; Márquez-García 2018). Pesticide and fertiliser application have shown to negatively impact upon vineyard biodiversity, especially where use is excessive, and can have downstream impacts within lakes and streams (Puig-Montserrat *et al.* 2017). Another benefit of encouraging biodiversity in vineyards is the aesthetic value species diversity add to the landscape, increasing values associated to community identity and human well-being (Tribot *et al.* 2018).

To inform the conceptual modelling (discussed in Section 9), expert opinion and existing research were used to determine the relationships between vineyard management, biodiversity, and ecosystem service delivery. More details can be found in Section 5.4.2 of the of the accompanying technical report.

6 Soils

Soils are a critical part of planet's natural system and controls biological, hydrological and geochemical cycles. Soils provide the nutrients, substrate and water that underpin natural and agro-ecosystems (Comino *et. al.* 2016). The soils of the Colchagua Valley are comprised of fine-textured loam clay and loam silt that are bordered by textured volcanic soil in the foothills (Viñas de Colchagua 2012). Soil quality determines the quantity of wine and quality of grapes (van Leeuwen *et al.* 2009; Ruiz-Colmenero *et al*. 2011, 2013)

Sustainably managed soils are living systems that contribute to water retention, reduced erosion and nutrient losses, and improved diversity of soil micro-organisms; all are important factors contributing to crop health. Vineyards are prone to high erosion rates, making soil erosion a critical part of management practices. Factors driving soil erosion in vineyards include steep slopes, disturbance of soil profile through planting and tillage practices, and soil compaction leading to decreased porosity and high run-off rates. Understanding soil dynamics is critical to informing long-term sustainable soil management (Comino *et. al.* 2016).

Soil erosion modelling uses data to demonstrate how soil processes operate at both a vineyard and landscape scale and can help predict changes under different management and land use scenarios. Models can form part of strategic ecosystem-based management planning, such as identifying areas to plant buffer strips and key upslope habitats which are critical to maintain in order to intercept surface runoff and prevent soil erosion.

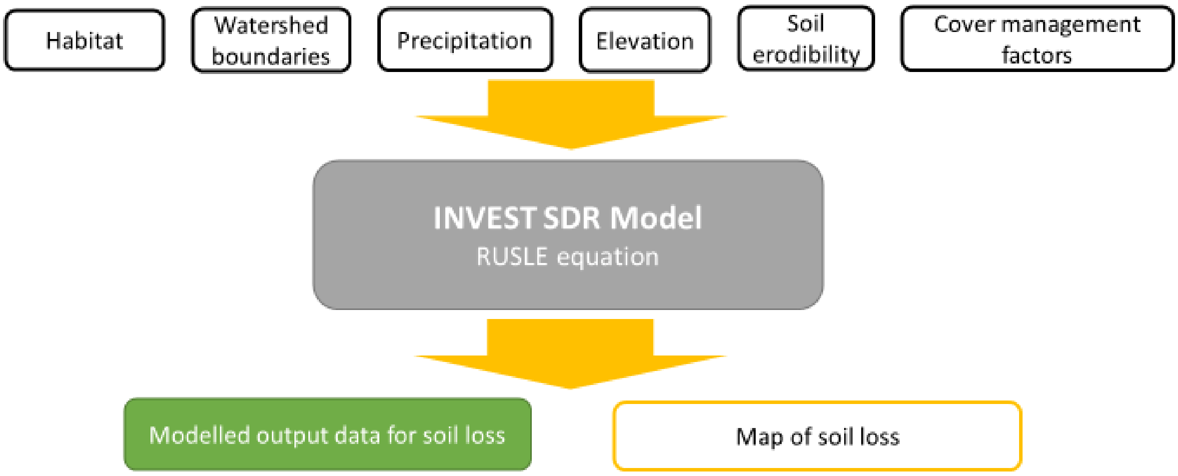

Figure 4. Representation of the soil modelling process undertaken to create soil loss model and map.

To evaluate the movement of soil from within and above vineyards, the soil model uses the Sediment Delivery Ratio (SDR) model of InVEST 3.5.0 to calculate the Revised Universal Soil Loss Equation (RUSLE). The SDR model maps the overland sediment generation and subsequent delivery to waterways, and outputs the total potential soil loss per pixel calculated from the RUSLE:

$$A=RKLSCP$$

where A is the rate of soil loss (ton ha^{-1} yr^{-1}), R is the annual rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t ha yr ha^{-1} MJ^{-1} mm^{-1}), L is the slope length factor, S is the slope steepness factor, C is the cover and management factor, and P is the supporting soil management practices factor. RUSLE equation does not include wind erosion, nor rill and gully erosion or landslips, and therefore the results are viewed as indicative and not absolute. More detail on the modelling approach can be found in Section 2 of the accompanying technical report.

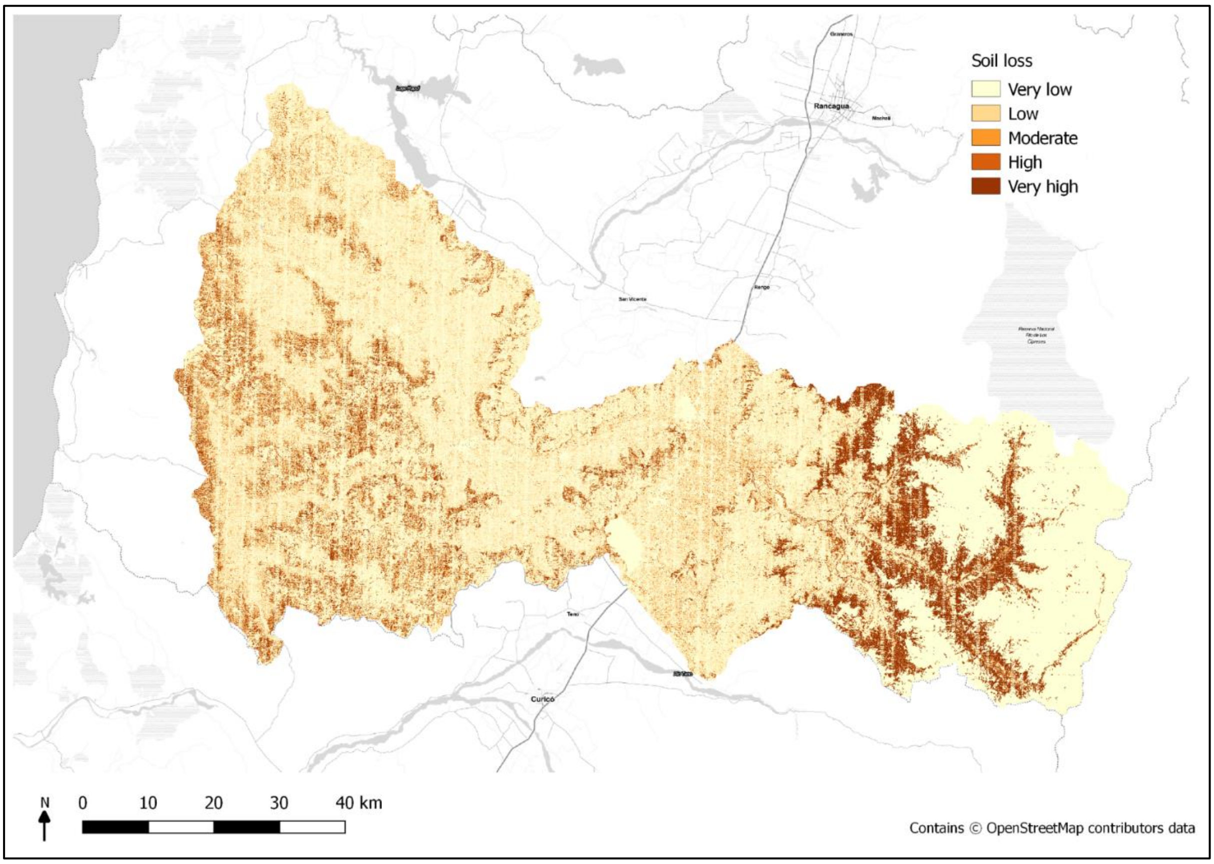

Figure 5. Map representation of the soil model output.

Table 2. Data used in soil modelling. All spatial data were georeferenced and cropped to the area of interest. Data processing and transformations were performed in in R version 3.4.4.

Climate Data: Minimum annual air temperature, maximum annual air temperature, mean annual air temperature, mean annual windspeed, and total annual precipitation were calculated from data downloaded from WorldClim v2.0. Meteorological station data was also provided by the vineyards for 2018 and additional stations from the Ministerio de Obras Püblicas's Direcciõn General de Aguas hydrometric network (DAG 2019) were added to improve hydrological estimations.

Future climate data under climate change scenarios: Data from two Intergovernmental Panel on Climate Change (IPCC) representative concentration pathway scenarios under CMIP5 representing moderate stabilization and very high baseline emission were taken from WorldClim v1.4.

Rainfall erosivity factor: This index describes the rainfall erosivity power, and the effect of raindrop impact on runoff. Rainfall intensity and erosion data were not available and therefore derived on equations based on the correlation between rainfall erosivity (R) and total precipitation.

Soil erodibility: Is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff, largely based soil texture. Soil profile data were taken from the harmonized continental SOTER-derived database that provides proportion of clay, silt and sand of the soil. UNFAO data was used to classify soil type based on the soil size and texture proportions.

Slope length and steepness: A digital elevation model was produced using NASA Shuttle Radar Topography Mission (SRTM) 2000 data and resampled to 10m resolution. Slope and steepness were then calculated from this data.

Land cover: Habitat map produced for the project using Sentinel-1 and Sentinel-2 data.

Cover management and support practice factors: These are factors applied to the defined land cover classes. The cover management factor reflects the effect of cropping and management practices on annual soil loss, and can be varied with differing management practices. The support practice factor specifies the ratio of soil loss in comparison to upslope and downslope tillage and is principally affected by practices such as contouring and terracing. Given the lack of local data regarding this factor, for the purposes of this study the model assumes no special practices are in effect.

Watersheds: This is the delineation of subbasins within the modelled region and were produced based on the HydroBASINS data layer (Lehner & Grill 2013).

7 Fire Susceptibility

In 2017 it was reported that over 200 km² of the Colchagua valley were burned by wildfires. Wildfires have significant ecological and socio-economic impacts. Identifying drivers that govern fire activity spatially and temporally is important to formulating landscape planning and management to mitigate the risks posed, whilst recognising the part fire plays in natural processes (Gomez *et al.* 2019).

Evidence suggests fire occurrence is closely tied to climate (temperature and precipitation) and land cover. As climate change shifts temperatures, this will likely alter fire regimes. Topography can affect fire directly by influencing its behaviour through the landscape, and indirectly by creating microclimate that governs spatial distribution of fire propensity. Human activities are a common source of ignition in Mediterranean-type ecosystems (Gomez *et al*. 2019).

Vegetation characteristics such as foliar flammability, fuel load, and plant structure can govern the likelihood of fire starting and the speed at which it spreads. Non-native forestry plantations (e.g. *Pinus radiata*, *Eucaliptus* sp.) in Chile have increased fire risk due to their high flammability, connectivity and low water content (Barbosa & Godoy 2014)

Habitats that tend to slow fire spread are native Sclerophyllous forest and "*Espino*" (*Acacia caven*). Sclerophyllous forests mainly comprise evergreen perennial plant species, which retain their leaves and maintain high levels of relative humidity and low temperature; both factors that reduce potential fire occurrence (CONAF 2018; Pauchard *et al*. 2008, Gómez-González *et al*. 2011).

Models can incorporate these multiple factors to improve understanding of the complex interactions which drive wildfire outbreak, helping to inform ecosystem-base management at different scales. The model employs a species distribution modelling (SDM) type framework, following previous studies in Chile and elsewhere that use historical burn and estimated ignition locations as presence points analogous to species records to identify environmental and anthropogenic predictors of wildfire. The models predict current landscape ignition susceptibility and burn avoidance (how unsusceptible the habitat is to catching fire), using Moderate Resolution Imaging Spectroradiometer (MODIS) burned area points to train a random forest regression model. More detail on the modelling approach can be found in Section 3 of the accompanying technical report.

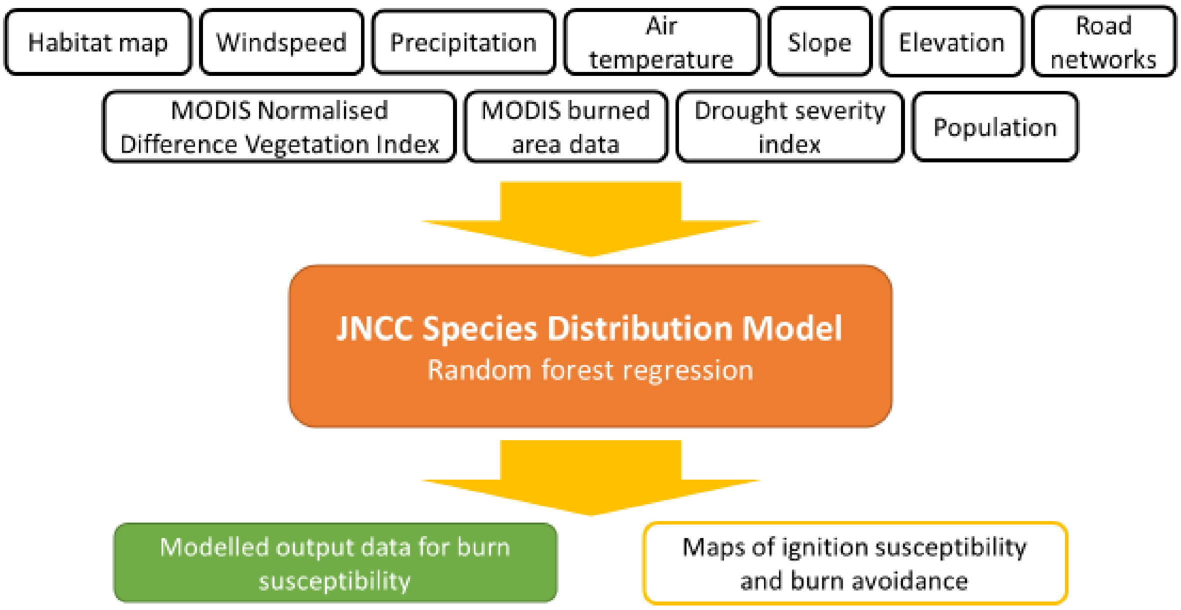

Figure 6. Representation of the fire modelling process undertaken to create ignition susceptibility and burn avoidance maps.

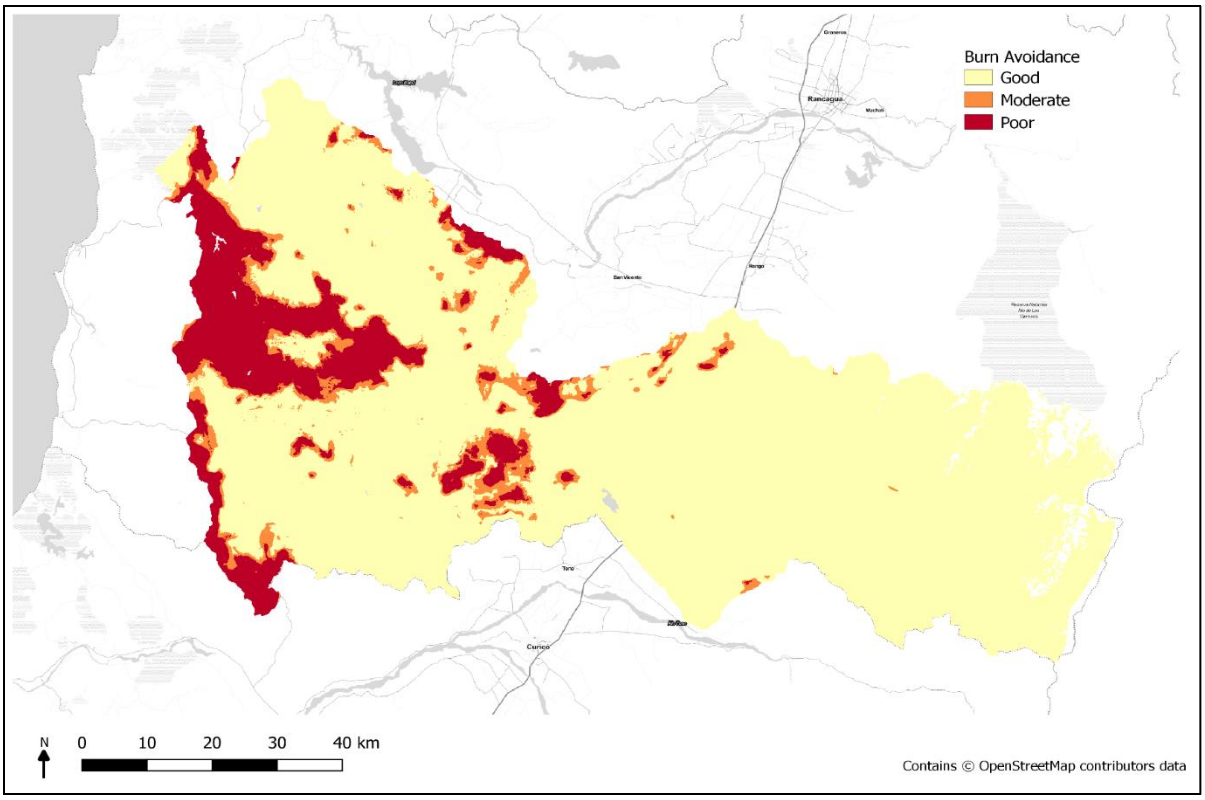

Figure 7. Representation of habitat burn avoidance, categorised as Good (>66% avoidance, least likely to burn), Moderate (33-66%) and Poor (<33% avoidance, more likely to burn).

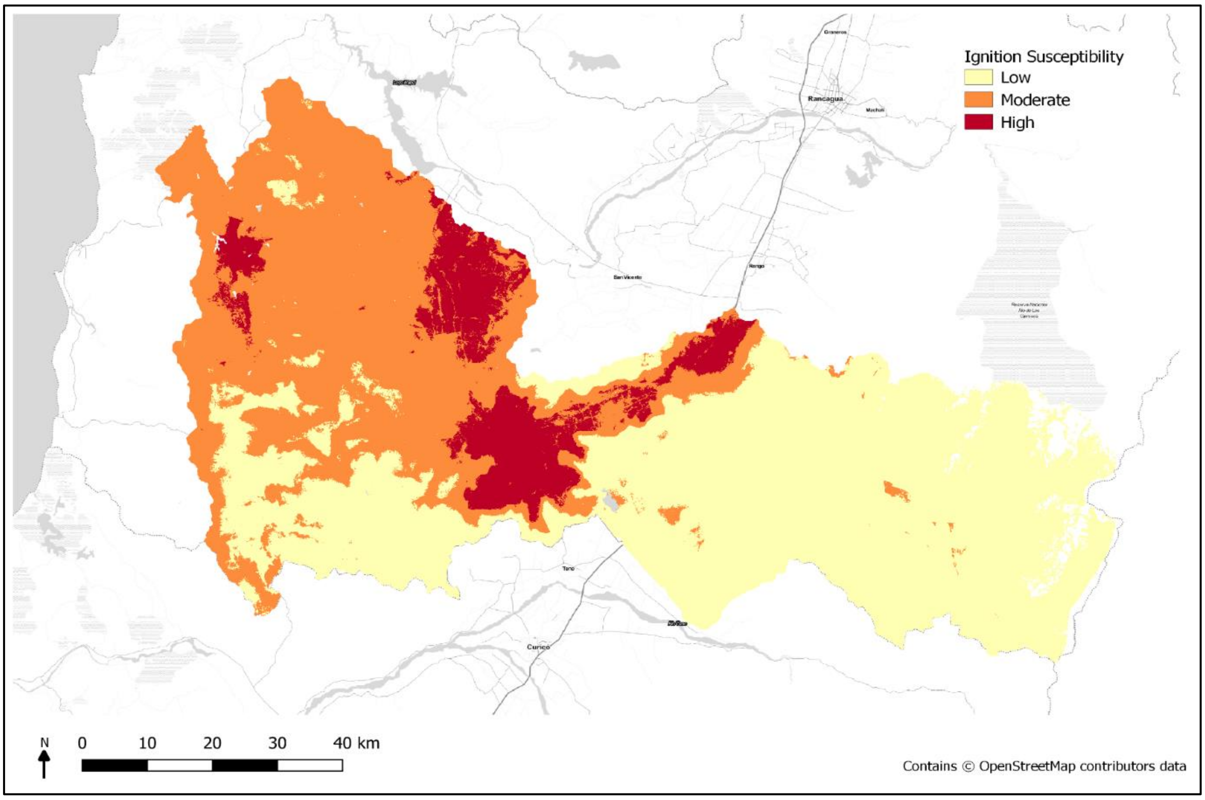

Figure 8. Representation of habitat ignition susceptibility, categorised as Low (<33% susceptibility, least likely to ignite), Moderate (33-66% susceptibility) and High (>66% susceptibility, most likely to ignite).

Table 3. Data used in fire modelling.

Topographic Data: A digital elevation model was obtained from NASA's Shuttle Radar Topography Mission (SRTM) 2000 data, and resampled to 10m resolution. Slope was derived from this data using QGIS 3.4.

Climate Data: Minimum annual air temperature, maximum annual air temperature, mean annual air temperature, mean annual windspeed, and total annual precipitation were calculated from data downloaded from WorldClim v2.0. Temperature and precipitation seasonality were also calculated from the Worldclim data. Global annual Palmer Drought Severity Index raster layers were downloaded from TerraClimate and provide information about potential habitat dryness and flammability. Meteorological station data was also provided by the VCCB stakeholders for 2018 and additional stations from the Ministerio de Obras Püblicas's Direcciõn General de Aguas hydrometric network (DAG 2019) were added to improve hydrological estimations.

Biological Variables: MODIS MOD13A1 Normalized Difference Vegetation Index (NDVI) product was used to model vegetation productivity and condition.

Land cover: Habitat map produced for the project using Sentinel-1 and Sentinel-2 data.

Anthropogenic Variables: Data layers capturing information on population density and the distance of burned and unburned areas to main roads. A shapefile of Chilean road networks was downloaded from OpenStreetMap and edited to include only significant roads. Modelled data of population density per hectare was obtained from WorldPop (2016), and rescaled to match to UN country-level population estimates.

Burned Area Data: Monthly MODIS burned area product MCD64A1 (Giglio *et al.* 2015) was downloaded and processed using R.

8 Water Quality and Supply

Water supply and water quality were highlighted as priority ecosystem services by stakeholders, being essential to grape production. Key aspects considered were water resource management under future climate scenarios and impacts on water quality driven by land management practices. Maintaining wine grape productivity and quality under future climate scenarios may be associated with increased water use through irrigation and misting or sprinkling to cool grapes. Industry adaptation and water conservation will be required to anticipate these possible effects (Hannah *et al.* 2013).

Environmental conditions and application methods influence how chemicals applied to agricultural crops are released and behave in the wider environment. For example, leaching of chemicals into deeper soil layers can occur following rainfall events and result in ground water contamination. Aerial application can result in high levels of surface water contamination through unintentional spray drift.

Stakeholders expressed a desire to understand how land management strategies involving fertiliser and pesticide application, soil tillage, creation and maintenance of buffer strips, and cover crops could have a bearing on water resources both now, and under future scenarios. Ecosystem mapping and modelling can help inform where ecosystem based management can be employed to maintain water quality by providing a understanding of hydrology and ecosystem processes important to water provisioning services, as well as the pathways that chemical pollutants can enter the environment and impact water quality. More detail on the modelling process can be found in Section 4 of the accompanying technical report.

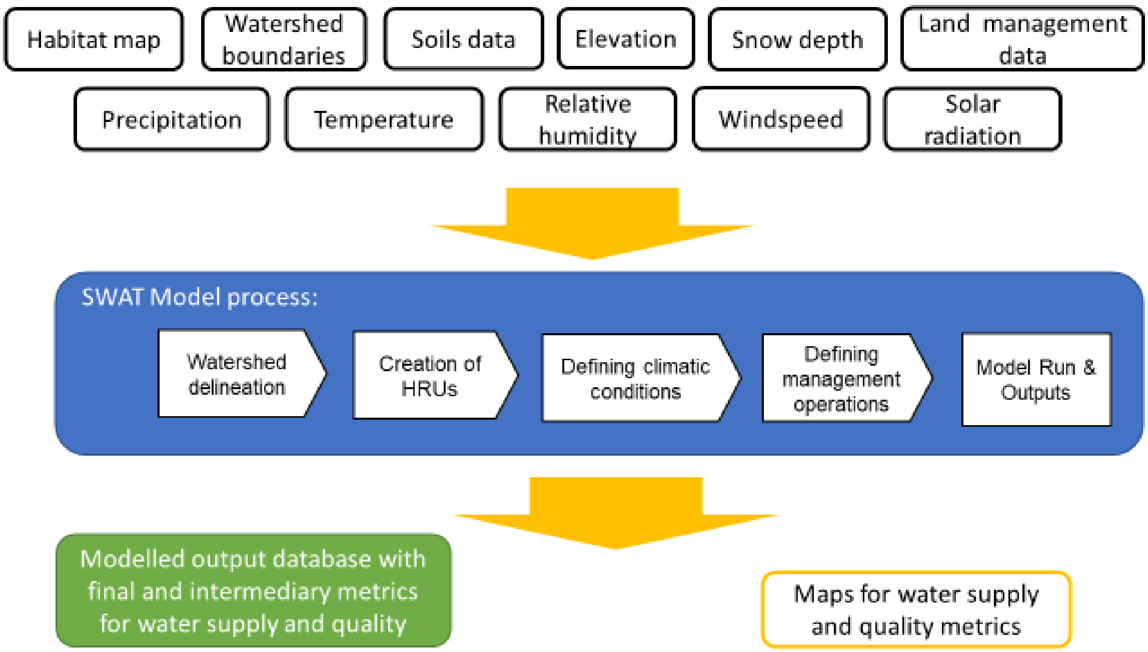

Figure 9. Representation of the water modelling process undertaken.

8.1 Modelling Colchagua Watershed

The Soil and Water Assessment Tool (SWAT) was used to model and map water metrics within the valley. SWAT is an open-sourced environmental model developed by the US Department of Agriculture, Agricultural Research Service (USDA-ARS) that has been used globally for assessing the daily, monthly and annual hydrological and sediment dynamics in a watershed. It is available through a QGIS interface and uses data inputs of elevation, land use and soil maps to delineate a watershed into sub-basins and determine Hydrological Response Units (HRUs) which are defined by all similar land uses, soils, and slopes within a sub-basin.

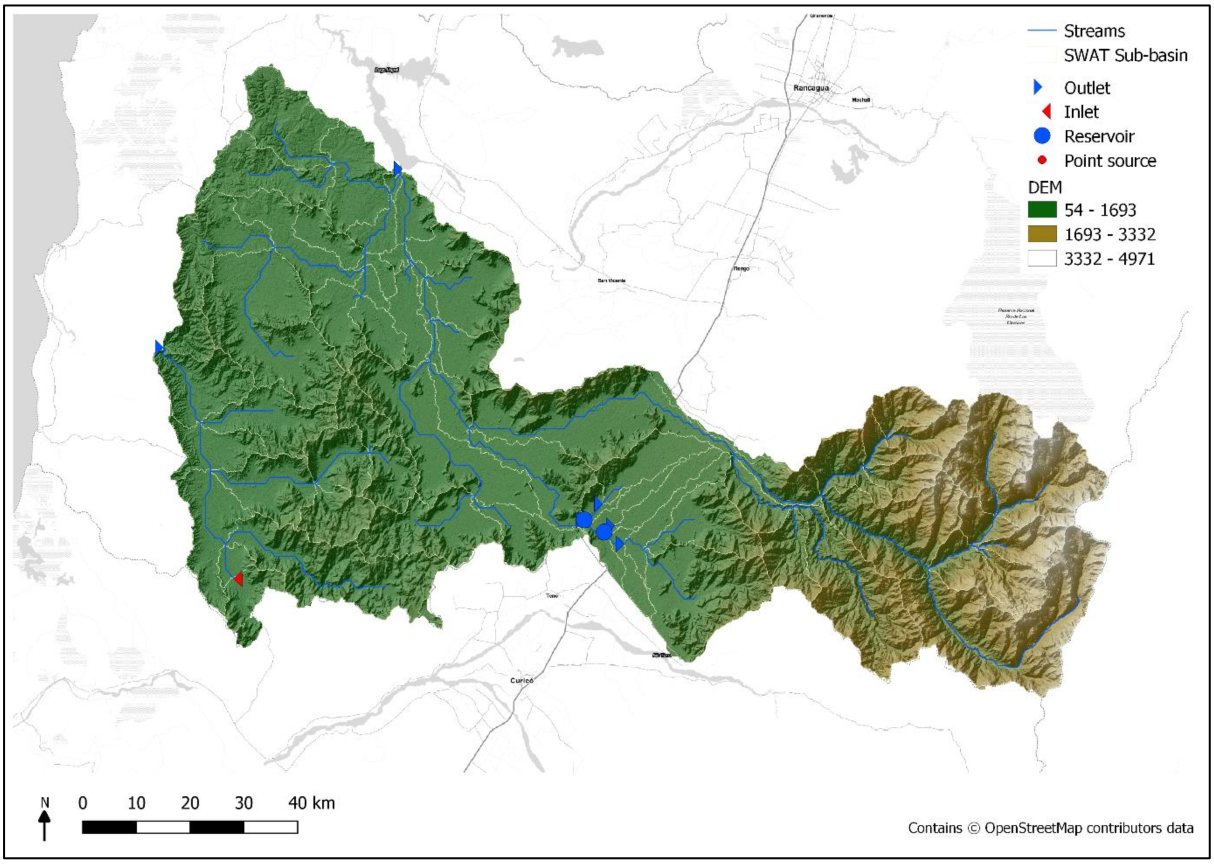

Figure 10. Delineated Watershed (depicted by white lines) overlaid on top of the digital elevation model.

8.2 Modelling Watershed Ecosystem Services

Once the watershed model was created it was possible to run baseline scenarios to simulate the hydrological flows across the landscape and generate metrics for the amount of water and nutrients held within the soil and streams. The statistical outputs generated by baseline models depict a scenario whereby no management (e.g. chemical input, tillage) are applied to the land. This provides the starting point from which to interrogate the potential effects land management has on ecosystem services.

Results are presented categorically with high, moderate and low values. The categorical boundaries are determined from the data ranges of the baseline model, as well as comparisons with literature resources for the ranges of meteorological variables in Central Chile (Boisier *et al.* 2018; Alvarez-Garreton *et al.* 2018).

The SWAT model was run with meteorological station data and long term historical weather statistics. The model was run firstly to show the baseline conditions which shows the ecosystem services delivered where no management measures are applied to the land. SWAT outputs produce a baseline map of annual water yield and average daily streamflow across the modelled period divided across Hydrological Response Units. The gridded appearance of the output maps reflects the low resolution of the UN FAO soils data layer used in the model.

Water yield (Figure 11) is the total amount of water leaving the HRU and entering the main channel. This calculated from surface water runoff, lateral flow, groundwater flow, transmission losses through tributary channels and water abstractions.

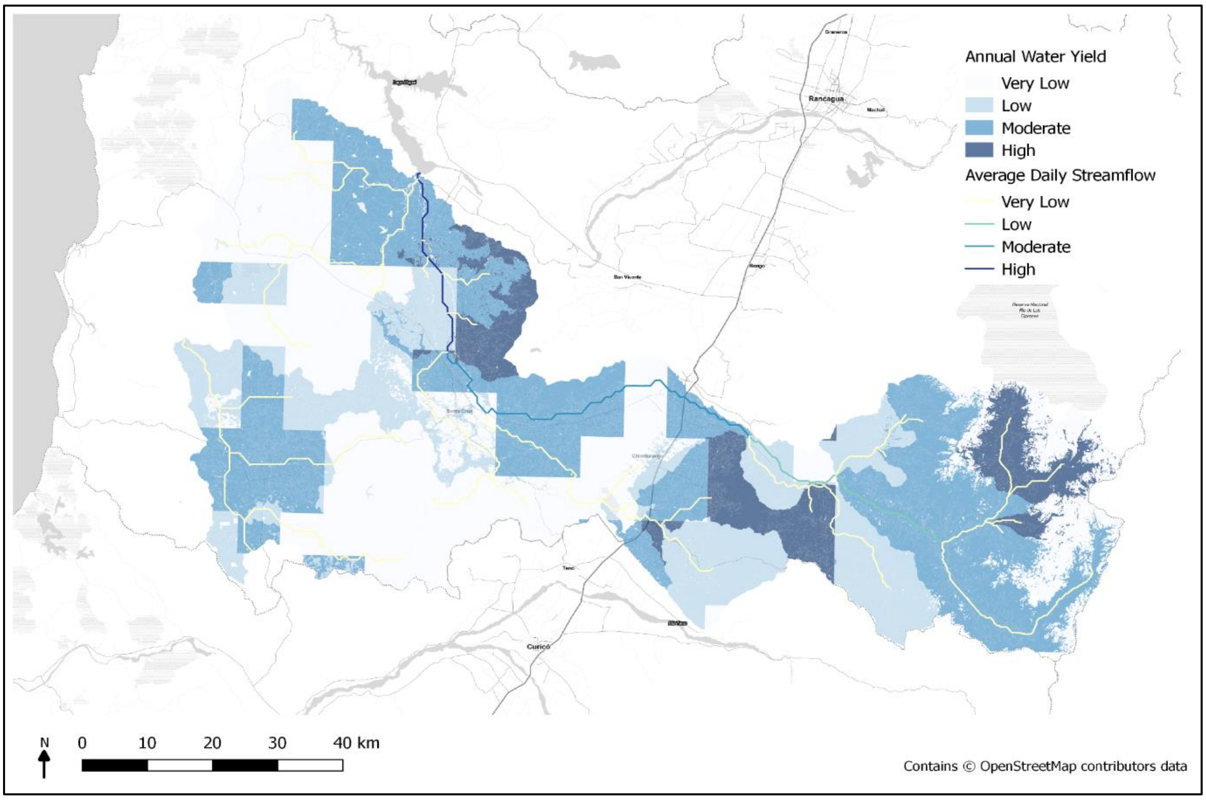

Figure 11. Baseline map of annual water yield and average daily streamflow across the modelled period divided across Hydrological Response Units.

The baseline map of annual mean percolation past the root zone (Figure 12) is based on the rooting depth associated with the crop type and is a calculated average annual value per HRU.

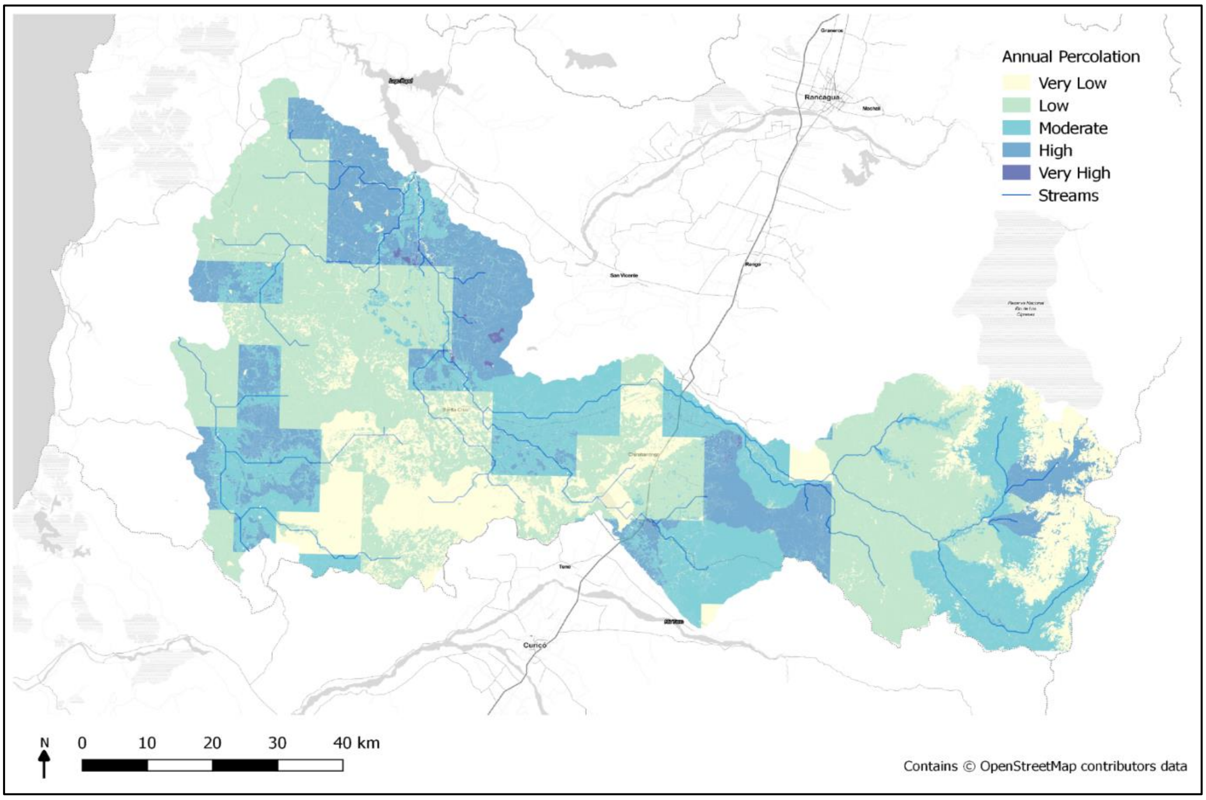

Figure 12. Baseline map of annual mean percolation past the root zone.

As data for the current levels of phosphates and nitrates present within streams were unavailable, determining the current state of water quality within the region proved challenging. To provide an indication of areas likely to have naturally higher nitrate and phosphate levels, and therefore at greater likelihood of having poorer water quality, the loading rates of organic nitrogen and phosphorus were mapped. These were calculated through equations used to model nitrogen and phosphorus cycles based on land use and soil characteristics (Neitsch *et al.* 2011). The categorised levels of nitrate and phosphorus present in the water are based on concentration classifications from the assessment for the nitrates directive in England (ADAS 2007) and the UK Technical Advisory Group on the Water Framework Directive European standards (2008).

Modelled outputs were used to produce maps of organic nitrogen and phosphorus loading rates, which depict where nutrients are leaving the Hydrological Response Units and entering the stream. The baselines are mapped against the natural levels of nitrate present in the water within each stream reach. These are estimations of natural levels without any additional management being applied to the landscape. The nitrogen and phosphorus yield maps are zoomed in to the major populated region in the south west of the Colchagua Valley where stakeholder vineyards are predominantly located.

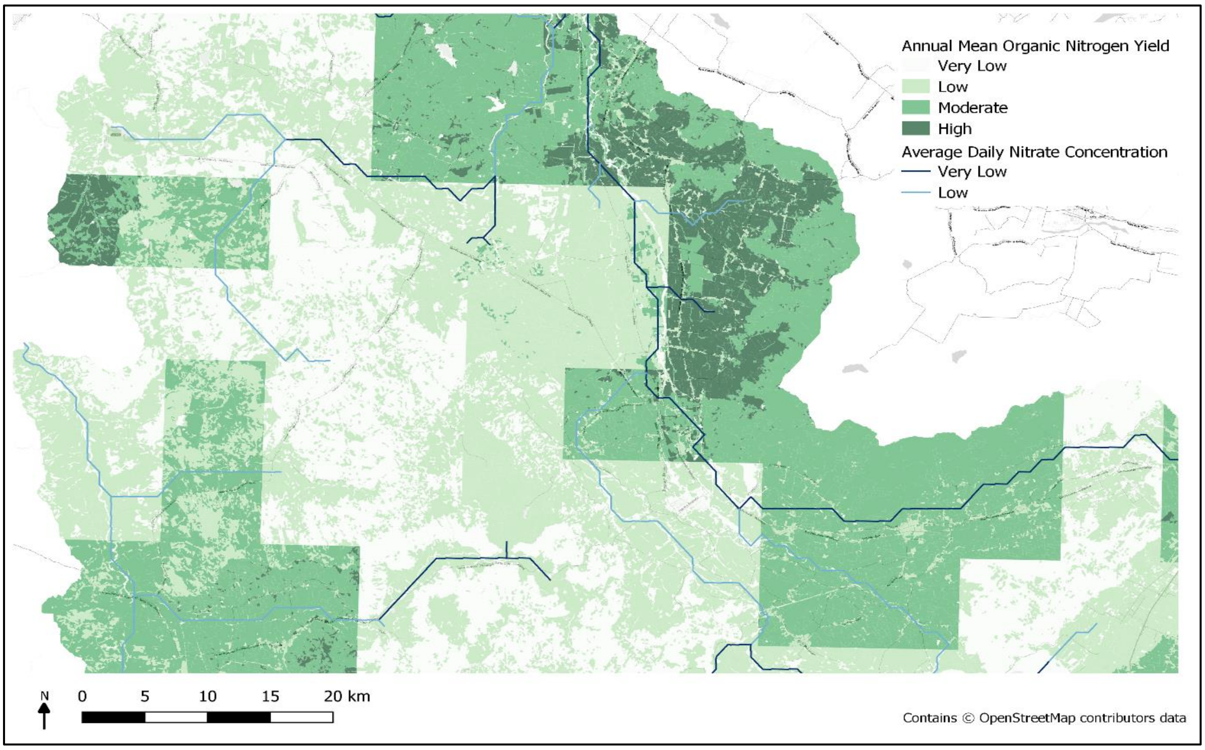

Figure 13. Map of modelled organic nitrogen loading rates, where nutrients are leaving the Hydrological Response Units and entering the stream. Map is zoomed in to the major populated region in the south west of the Colchagua valley where stakeholder vineyards are predominantly located.

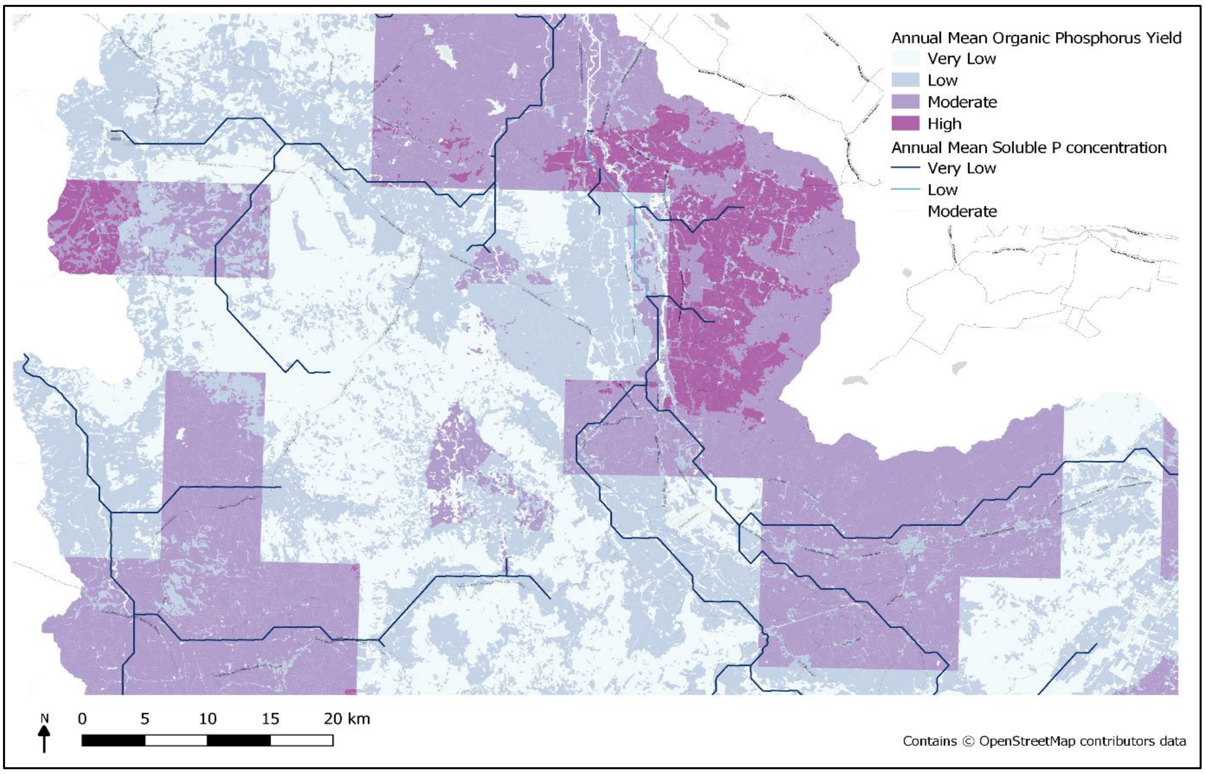

Figure 14. Map of modelled organic phosphorus loading rates, where nutrients are leaving the Hydrological Response Units and entering the stream. Map is zoomed in to the major populated region in the south west of the Colchagua valley where stakeholder vineyards are predominantly located.

8.3 Modelling Water Stress Under Climate change scenarios

Water stress is used in viticulture to increase the fruit quality of berries, however if crops are in water deficit conditions then this can significantly reduce the production yield (Jara *et al*. 2017). Climatic conditions of vinicultural areas, including humidity and water stress, may also influence the microbial diversity and thus terroir, potentially contributing to the distinctive properties of wine from each region (Jara *et al*. 2016).

Maps of potential water stress days experienced under climate change scenarios were produced to help inform vineyard owners on how water availability may change in the future to gauge the potential impact this can have on vines. Water stress is calculated as a function of the amount of water uptake of the plant during the day and the maximum amount of transpiration.

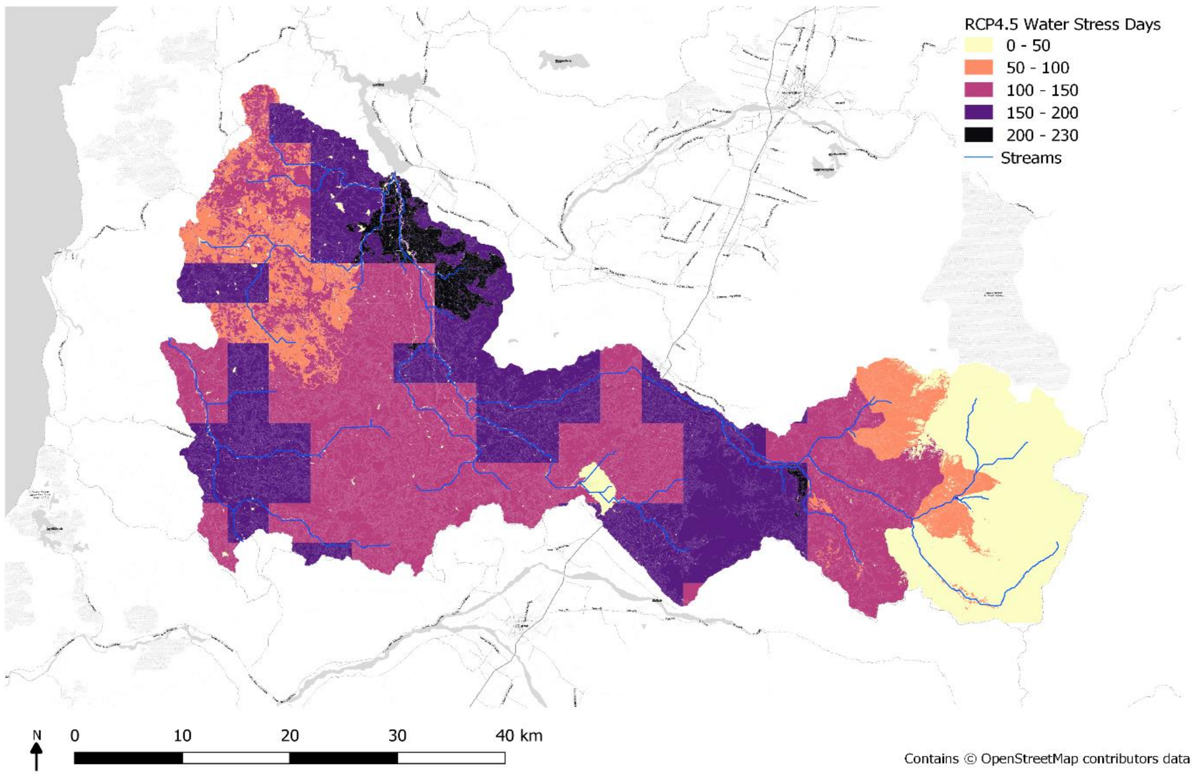

Figure 15. Modelled representation of water stress days experienced under climate change scenario RCP4.5 which represents a moderate stabilization scenario under climate change.

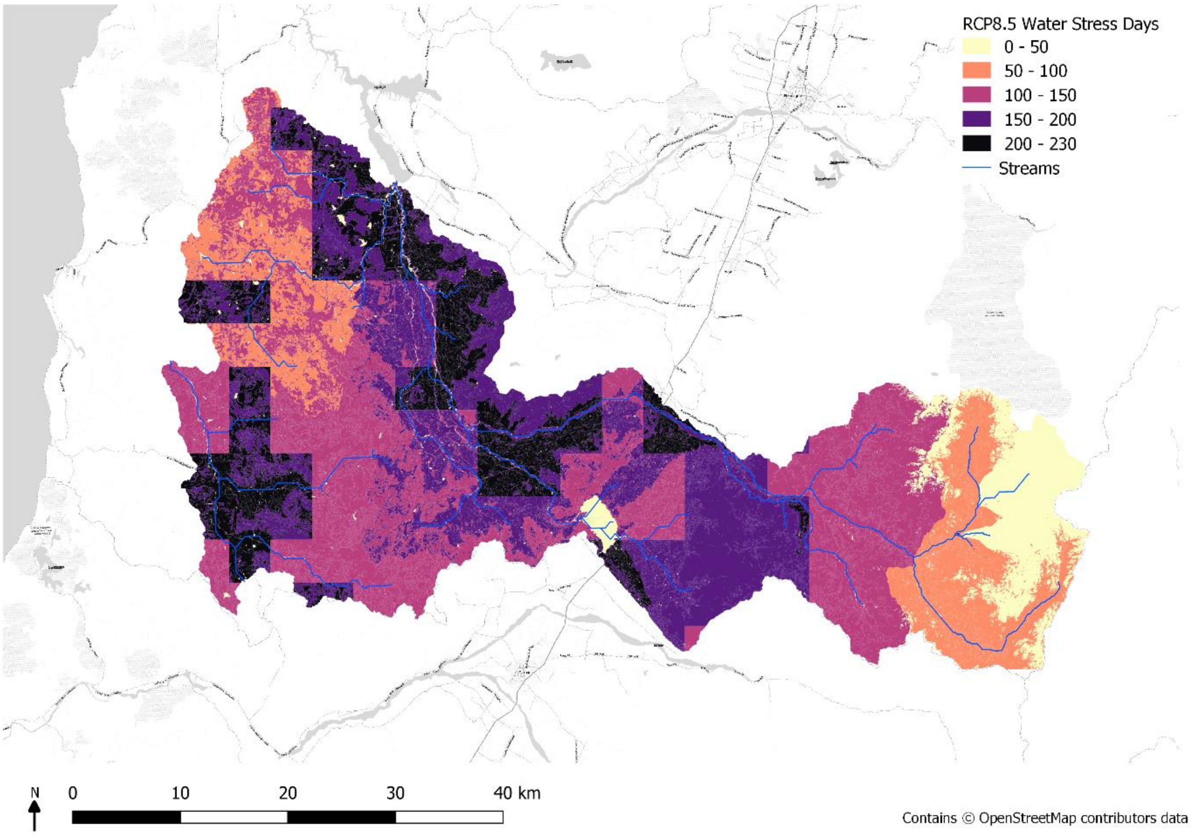

Figure 16. Modelled representation of water stress days experienced under climate change scenario RCP 8.5, representing a very high baseline emissions scenario.

Table 4. Data used in watershed modelling

Landscape: A Digital Elevation Model provided by NASA's Shuttle Radar Topography Mission (SRTM) in 2000. The SRTM data is open source and is available at 30 m resolution.

Watershed: High level watershed delineation boundaries were obtained from Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) developed by the World Wildlife Fund's Conservation Science Program (WWF 2019).

Land cover: Habitat map produced for the project using Sentinel-1 and Sentinel-2 data.

Soils: A South American soil tile was obtained from Waterbase (UNU-INWEH 2019) based on the UN Food and Agriculture Organization (FAO) digitized Soil Map of the World (2003).

Climate: Local data were provided from five vineyard weather stations for 2018 with incomplete daily records for variables including; daily air temperature, precipitation, relative humidity, solar radiation and wind speed. Additional stations from the Ministerio de Obras Püblicas's Direcciõn General de Aguas hydrometric network (DAG 2019) were added to improve hydrological estimations.

Long term climate: Records from the Climate Research Unit East Anglia CRUTS3.1 dataset (Harris *et al.* 2014; Vaghefi *et al*. 2017) and from the National Centres for Environmental Prediction's Climate Forecast System Reanalysis (NCEP-CFSR) global meteorological dataset through SWAT's weather data tool (2019) were used to develop a weather generator for the model.

Climate change scenarios: Climate data for climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) evaluations that were used in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) for two climate change scenarios (RCP 4.5 and 8.5) were assessed. Data for daily mean air temperature and precipitation were obtained from 2W2E (2019) which extracted data from the ISI-MIP project that developed a Climate Change Toolkit for projecting and extracting predictive data under the CMIP5 scenarios (Vaghefi *et al.* 2017).

Snow depth: Snow depth data were obtained from experimental snow stations deployed in a study by Stehr and Aguayo (2017).

9 Conceptual Ecological Modelling – Bayesian Belief Networks

Previous research conducted by project partners at the Wine, Climate Change and Biodiversity Program, coupled with expert knowledge gathered through a workshop with the partner vineyards, provided an understanding of the different management approaches and an insight into how viticulturists in the region viewed relationships between management and ecosystem services.

A Bayesian Belief Network (BBN) approach was used to demonstrate how their suggested management practices impact upon ecosystem service delivery. This method was chosen as it allows for a flexible approach to integrate knowledge from the different modelled outputs. BBNs are a statistical modelling methodology used to infer probable relationships between elements using known relationships with intermediaries. A simple BBN diagram is displayed in Figure 17.

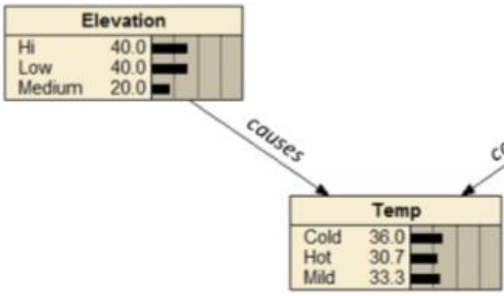

Figure 17. An example of a simple BBN diagram (Morgan *et al.* 2012)

Each component in the network is listed as an individual "node" and the relationship between the nodes are termed an "edge". The direction of the edge indicates causality, where one "parent" node can cause a change in state of the "child" node. In figure 17, this is illustrated by the season and elevation nodes determining the temperature.

Management practices suggested by VCCB (Barbosa & Godoy 2014) and key ecosystem services highlighted by the stakeholders were each assigned to a node. This was developed into a Directed Acyclic Graph (DAG) shown in Appendix 1, by adding additional nodes for intermediate environment components and edges to denote the relationships between nodes. Information on the states of each node and their conditional probability tables were informed by a mixture of measured and modelled data, literature reviews and expert opinion.

To make the BBN more accessible for stakeholders, an R shiny application was developed using R shiny dashboard, to allow users to view the outcomes of management decisions in a user-friendly display (see Section 7). More detail on BBN development can be found in Section 5 of the accompanying technical report.

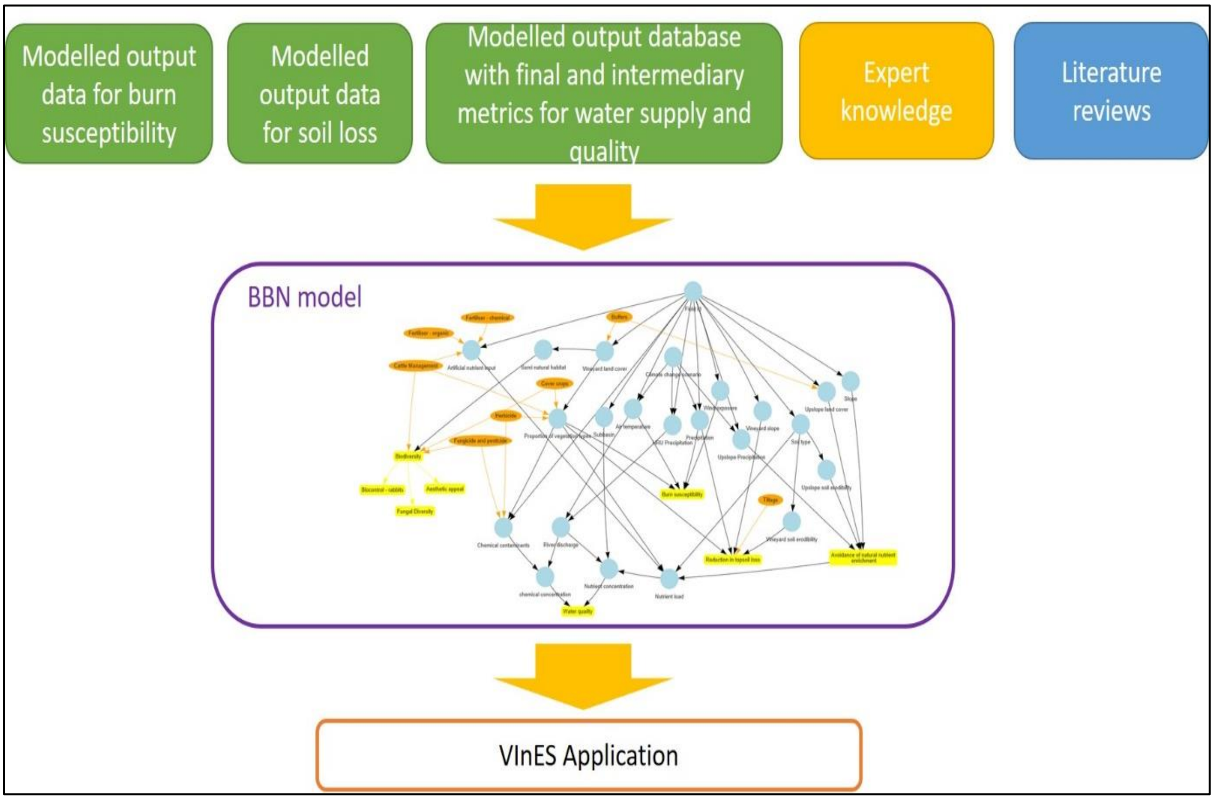

Figure 18. Conceptual modelling process adopted to link models to develop the VINES Application.

10 Applying the Bayesian Belief Network

The Viticulture ImplemeNting Ecosystem Services (VINES) application was developed using an R shiny dashboard to enable users to interrogate the BBN. It provides an example as to how data can be packaged in a format that can help inform land management decisions. The application enables users to select management practices and see how these impact upon the ecosystem service delivery at an individual field scale. This lets vineyard managers explore the relationships between management and ecosystem service delivery and the different trade-offs that could impact their businesses on a scale relevant to their operations.

The VINES application consists of three tabs, shown in the screenshots in Figure 19 to 21. The landing page (Figure 19) displays a 3D rendered image of the Colchagua valley. On the landing page users can select their winery and then a specific field, which will display their field in the context of the landscape in a 3D rendered image (Figure 20). This information then feeds into the second tab 'Management', which allows vineyard managers to view and query the data for their selected field, plotting the ecosystem service delivery in a coloured bar plot (Figure 21). Here users can select different management options and climate change scenarios, which queries the BBN and outputs how management is likely to change ecosystem services, with relative probabilities being displayed as either 'Good', 'Moderate' or 'Poor'. This is visualised by changes in the proportional bar plot. The bar plot is interactive, allowing users to hover over areas of the graph to retrieve probability values, as well as show and hide legend entries by clicking them. There is also an option to download a .csv file of the plot data and reset all management options to default. The final tab 'Network' displays the Bayesian Belief Network Directed Acyclic Graph, showing the user the mechanisms by which each scenario is affecting the ecosystem services and allows them to visualise the underlying BBN network.

The VINES Application is available online at: https://jncc.gov.uk/our-work/chile-viticulture-project-introduction/. More detail on the development of the application can be found in the accompanying technical report

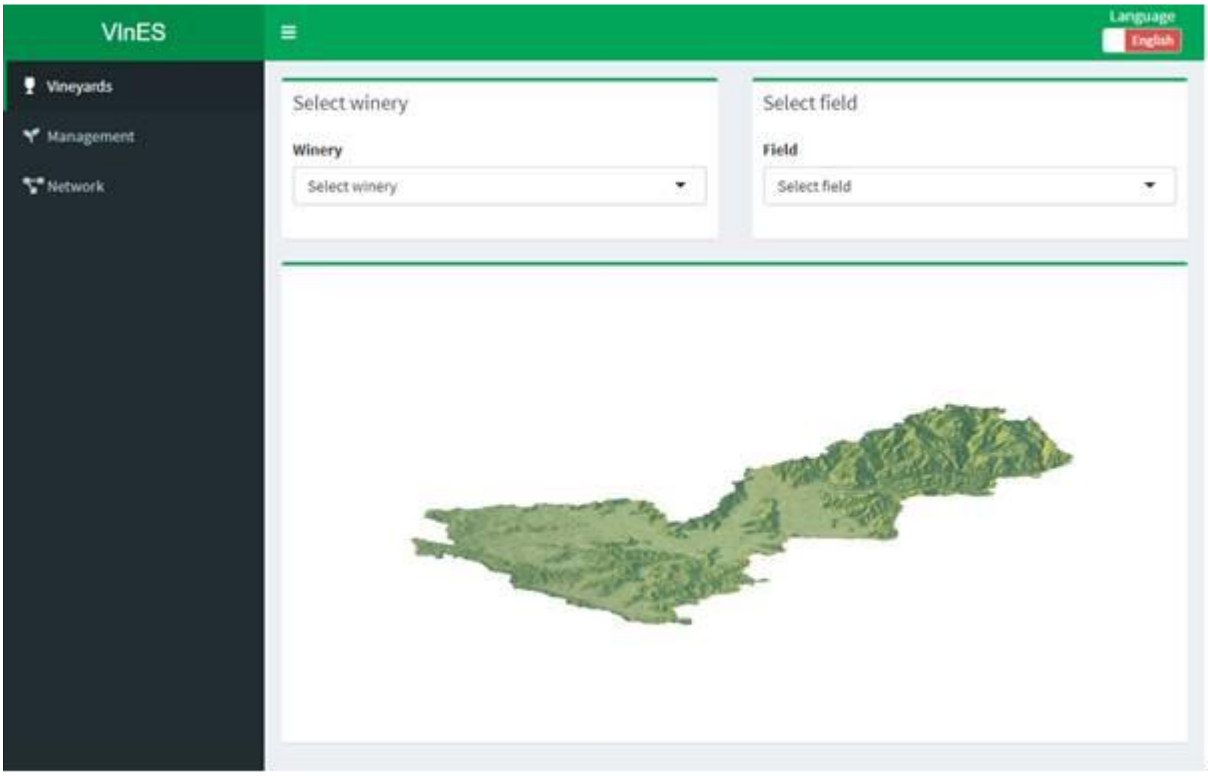

Figure 19. VINES Application landing page showing rendered image of the Colchagua Valley.

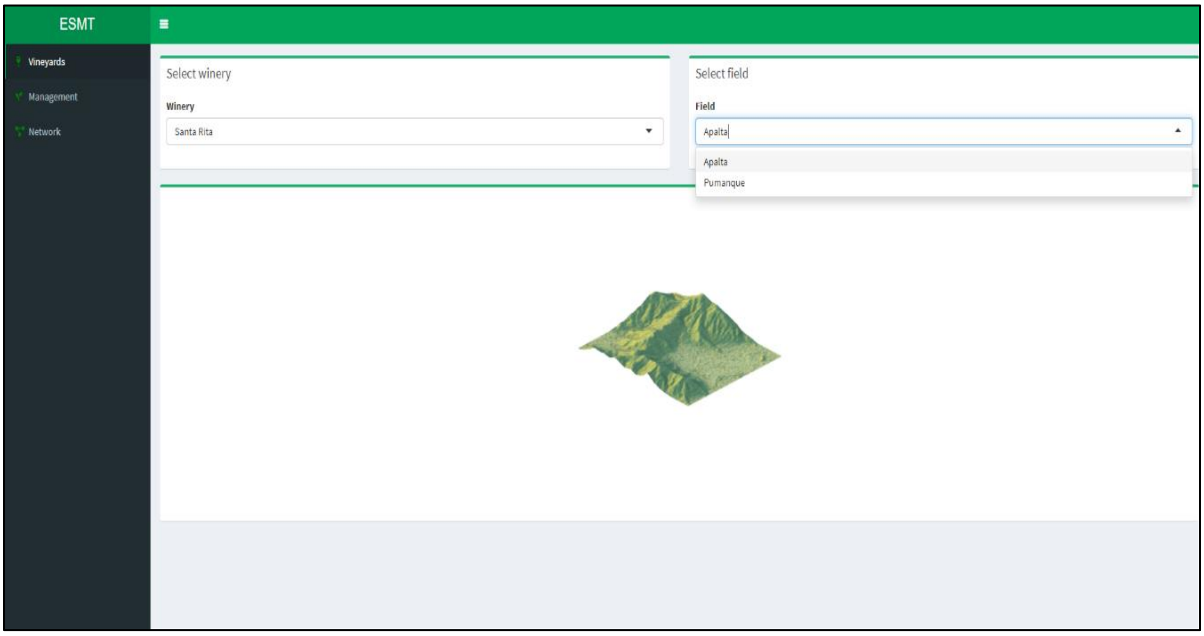

Figure 20. View for a selected vineyard and field combination.

Figure 21. Example plot displayed in the app, with default management and climate change options. The bars alter to show how management and climate variables results in good, moderate or poor ecosystem service delivery at the field level.

11 Conclusion and Next Steps

This pilot project was conducted over five months and should be considered as a proof of concept that demonstrates how it is possible to combine industry and local knowledge with ecosystem sciences to demonstrate the interactions between land management, biotic and abiotic factors and the effect on business-critical ecosystem services. As the models have not been validated, outputs should be treated as indicative and not absolute.

Due to the lack of local data, models are largely based upon regional and national data. Nonetheless, the project defines the type of data and information that is required to improve the accuracy of the models to enable them to be applied with greater confidence in a local management context. With more time and resources a second phase could work more closely with vineyard managers to source the data needed, and develop models further, adapting them to more localised conditions.

Whilst the models provide a useful indication of ecological processes and the drivers that alter their function and subsequent delivery of ecosystem services, they do not replace the need for on-the-ground monitoring and evaluation of land management interventions. They provide an indication as to where interventions are most likely to conserve or restore ecosystem services, which enables vineyards to make informed decisions as to how investment in ecosystem-based management can improve resilience of the vineyard and the surrounding landscape upon which they rely.

The approaches developed and demonstrated here can be adapted to other scenarios, ecosystem services and land uses, the main proviso being the availability of data.

11.1 Potential Steps for Model Improvement

Working more closely with vineyards to gather and apply local data and develop scenarios relevant to their field applications would help to gain a more detailed understanding of the links between management decisions, ecosystem responses, abiotic variables and impacts. This would not only help to improve the BBN performance but increase the accuracy of the output information that is produced. For instance, due to a lack of available data on current management practices adopted by the focal vineyards, conditions were modelled without considering practices already in place. Each vineyard was reviewed in isolation, and it is assumed that management from one vineyard does not impact management at another. Improved understanding of current interventions implemented by vineyards and other land users would provide a better picture of inter-play between different activities, potentially identifying opportunities for cooperative management to maximise ecosystem services and minimise environmental impacts.

Inputting more locally relevant and accurate data would better inform the models, which in turn result in the BBN providing improved indications of the effects of local management decisions on ecosystems. As well as data availability, there were data gaps in the local meteorological data provided by the stakeholders. These were inconsistent in their time intervals and missing several of the environmental variables required by the models in order to accurately simulate the weather in the valley.

Additional ground truthing points from field surveys could help improve the validation of the habitat map across a wider area. This would improve the accuracy of the classification of different land uses and help to better inform the ecosystem service mapping, and to detect change over time. The use of very high-resolution satellite imagery (>10 m resolution) would also improve habitat mapping.

Due to the paucity of local soils data, a low-resolution Food and Agriculture Organisation (FAO) soils data layer has been used, which does not accurately reflect how the soil compositions may vary spatially across the landscape. The soils data could be improved with the provision of local data or sampling, especially in terms of biophysical characteristics and rates of soil loss.

Other assumptions in the models were introduced where local crop characteristics and measurements were unavailable and instead were matched to the nearest crop type in the models' crop databases, which are based upon temperate USA crop types. Information on local crop characteristics would improve the accuracy of assessing factors such as water demand and stress and soil permeability.

With more time, a sensitivity analysis could be conducted to assess the relative influence the data layers and their spatial resolutions had upon the model outcomes, aiding in their performance and predictive ability. Furthermore, the models were unvalidated, as data was unavailable to test model predictive performance, and hence were provided as illustrative categorical data. If actual measurements were provided and model validation conducted, values could be demonstrated to stakeholders, producing a more meaningful outcome.

The models were limited in the scalability of their outcomes, for instance outputs of the SWAT model were produced on a hydrological response unit (HRU) scale. Further consideration could be made to identify management unit specific applications, a Biodiversity is of utmost importance to the terroir of the wine growing region. Researching organisms such as wild yeasts and soil microbial communities could be how modelled outcomes can be produced at a scale relevant to stakeholders.

Due to time and resource constraints it was not possible to cover all ecosystem services identified as ‘important’ by stakeholders. Future work could further explore natural biocontrol of pest species and develop the relationships with these ecosystem services and the environmental components based on further literature reviews. Cultural values associated with the vineyards and landscape could also be incorporated in future work. explored in relation to land management and spatial planning to maintain or restore unique characteristics of the landscape.

The ecosystem service models and Bayesian Belief Network that has been developed in this project can be used to inform environmental monitoring schemes, assess outcomes in real terms, such as whether reduced cattle stocking density impacts soils or water quality and provide useful information to inform landowners about sustainable management decisions. There is potential in the future to further develop this work and explore how this type of information can be quantified and used by producer organisations to help their growers meet the sector’s potential and to improve and report on environmental performance.

12 References

ADAS. 2007. Nitrates in water – the current status in England. ADAS report to Defra – supporting paper D1 for the consultation on implementation of the Nitrates Directive in England. July 2007.

Alvarez-Garreton, C., Mendoza, P.A., Boisier, J.P., Addor, N., Galleguillos, M., Zambrano-Bigiarini, M., Lara, A. Puelma, C., Cortes, G., Garreaud, R, McPhee, J. & Ayala, A. 2018. The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies – Chile dataset. *Hydrology and Earth System Sciences* **22**: 5817-5846. https://doi.org/10.5194/hess-22-5817-2018.

Barbosa, O. & Godoy, K. 2014. Conservación biológica en viñedos: conceptos claves y actividades practices. Programa Vino Cambio Climático y Biodiversidad Chile. Universidad Austral de Chile 2014.

Boisier, J.P., Alvarez-Garreton, C., Cordero, R.P., Damiani, A., Gallardo, L., Garreaud, R.D., Lambert, F., Ramallo, C., Rojas, M.,Rondanelli, R. 2018. Anthropogenic drying in central-southern Chile evidenced by long-term observations and climate model simulations. *Elementa Science of the Anthropocene* 6: 74. DOI: https://doi.org/10.1525/elementa.328.

Bravo, C., Loriaux, T., Rivera, A. & Brock, B.W. 2017. Assessing glacier melt contribution to streamflow at Universidad Glacier, central Andes of Chile. *Hydrology and Earth System Sciences* **21**(7):3249-3266.

CBD. 2018. Convention on Biological Diversity. Guidelines for Ecosystem-based Approaches to Climate Change Adaptation and Disaster Risk Reduction. Available at: https://www.cbd.int/sbstta/sbstta-22-sbi-2/EbA-Eco-DRR-Guidelines-en.pdf [Accessed 09/06/2019].

CICES. 2018. Common International Classification of Ecosystem Services Version 5.1. Available at: https://cices.eu/ [Accessed 09/06/2019].

Comino, R.J., Quiquerez, A., Follain, S., Raclot, D., Le Bissonnais, Y., Casalí, J., Giménez, R., Cerdà, A., Keesstra, S.D., Brevik, E.C., Pereira, P., Senciales, J.M., Seeger, M., Ruiz Sinoga, J.D. & Ries, J.B. 2016. Soil erosion in sloping vineyards assessed by using botanical indicators and sediment collectors in the Ruwer-Mosel valley. Agriculture, Ecosystems & Environment. 233, 158-170.

CONAF. 2018. Plantas y combustibles vegetales en la ignicion y propagacion inicial del fuego. Region del Libertador General Bernardo O'Higgins, Chile.

Direcciõn General de Aguas (DAG), Ministerio de Obras Públicas. 2019. Información Oficial Hidrometeorológica y de Calidad de Aguas en Línea. Available from: http://snia.dga.cl/BNAConsultas/ reportes 2015-2018 [Accessed 13/01/2019].

Giglio, L., Justice, C., Boschetti, L. & Roy, D. 2015. MCD64A1 MODIS/Terra+Aqua Burned Area Monthly L3 Global 500 m SIN Grid V006. 2015, distributed by NASA EOSDIS Land Processes DAAC. Available from: https://doi.org/10.5067/MODIS/MCD64A1.006 [Accessed 06/01/2019].

Gomez-Gonzalez, S., Torres-Diaz, C., Valencia, G., Torres-Morales, P., Cavieres, L.A. & Pausas, J.G. 2011. Anthropogenic fires increase alien and native annual species in the Chilean coastal matorral. Diversity and Distributions. 2011; 17(1):58±67. https://doi.org/10.1111/J.1472-4642.2010.00728.X.

Gómez-González, S., González, M.E., Paula, S., Díaz-Hormazábal, I., Lara, A. & Delgado-Baquerizo, M. 2019. Temperature and agriculture are largely associated with fire activity in Central Chile across different temporal periods. Forest Ecology and Management 433: 535-543.

Grashof-Bokdam, C.J. & van Langevelde, F. 2005. Green veining: landscape determinants of biodiversity in European agricultural landscapes. *Landscape Ecology* 20: 417-439.

Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Shaw, M.R., Tabor, G., Zhi, L., Marquet, P.A. & Hijmans, R.J. 2013. Climate change, wine, and conservation. PNAS 110 (17): 6907–6912. https://www.pnas.org/content/pnas/110/17/6907.full.pdf [Accessed 05/06/2019].

Harris, I., Jones, P.D., Osborn, T.J. & Lister, D.H., 2013. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology* 34(3): 623e642.

Jara, J., Holzapfel, E.A., Billib, M., Arumi, J.L., Lagos, O. & Rivera, D. 2017. Effect of water application on wine quality and yield in 'Carménère' under the presence of a shallow water table in Central Chile. Chilean Journal of agricultural research 77(2): http://dx.doi.org/10.4067/S0718-58392017000200171.

Jara, C., Laurie, V.F., Mas, A. & Romero, J. 2016. Microbial Terroir in Chilean Valleys: Diversity of Non-conventional Yeast. Frontiers in Microbiology 7: 663.

JNCC. 2019. Natural Capital in the Caribbean and South Atlantic Overseas Territories: Valuation, Vulnerability and Monitoring Change. Available at: http://jncc.defra.gov.uk/default.aspx?page=7443 [Accessed 09/06/2019].

Journet, G. 2016. Viticulture and ecosystem services: from myths to reality with Chilean vine growers. Master's Thesis 2016 30 ECTS. Department of Plant Sciences, Norges Milje-of biovitenskapelige universitet.

Márquez-García, M., Jacobson, S.K. & Barbosa, O. 2018. Wine with a Bouquet of Biodiversity: Assessing Agricultural Adoption of Conservation Practices in Chile. Environmental Conservation page 1 of 9. doi:10.1017/S0376892918000206.

MOD13A1 Version 6. Available at: https://lpdaac.usgs.gov/products/mod13a1v006/ [Accessed 09/06/2019].

Morgan, J.D., Hutchins, M.W., Fox, J. & Rogers, K.R. 2012. A Methodological Framework focused on integrating GIS and BBN Data for Probabilistic Map Algebra Analysis. *7th International Conference, GIScience, Columbus, OH*.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R. & Williams, J.R. 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. *Texas Water Resources Institute Technical Report* No.406. September 2011.

Pauchard, A., Garcia, R.A., Pena, E., Gonzalez, C., Cavieres, L.A. & Bustamante, R.O. Positive feedbacks between plant invasions and fire regimes: *Teline monspessulana* (L.) K. Koch (Fabaceae) in central Chile. Biological Invasions. 2008; 10(4):547±53. https://doi.org/10.1007/S10530-007-9151-8.

Puig-Montserrat, X., Stefanescu, C., Torre, I., Palat, J., Fábregas, E., Dantart, J., Arrizabalaga, A. & Flaquer, C. 2017. Effects of organic and conventional crop management on vineyard biodiversity Agriculture, Ecosystems and Environment. *Agriculture, Ecosystems and Environment* 243: 19–26.

Ruiz-Colmenero, M., Bienes, R. & Marques, M.J., 2011. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. Soil Tillage Res. 117, 211–223. http://dx.doi.org/10.1016/j.still.2011.10.004.

Ruiz-Colmenero, M., Bienes, R., Eldridge, D.J. & Marques, M.J., 2013. Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. Catena 104, 153–160. http://dx.doi.org/10.1016/j.catena.2012.11.007.

Simoes, A.J.G. & Hidalgo, C.A. 2011. The Economic Complexity Observatory: An Analytical Tool for Understanding the Dynamics of Economic Development. Workshops at the Twenty-Fifth AAAI Conference on Artificial Intelligence. Available at: https://atlas.media.mit.edu/en/profile/country/chl/ [Accessed 09/06/2019].

Tribot, A.S., Deter, J. & Mouquet, N. 2018. Integrating the aesthetic value of landscapes and biological diversity. Proc Biol Sci. 285(1886):2018.0971.

TerraClimate Available at: http://www.climatologylab.org/terraclimate.html [Accessed:11.06.2019].

UK Technical Advisory Group (UKTAG) on the Water Framework Directive (WFD). 2008. UK Environmental Standards and Conditions (Phase 1) Final report April 2008 (SR1 – 2006). Available from: http://www.wfduk.org/sites/default/files/Media/Environmental%20-standards/Environmental%20standards%20phase%201_Finalv2_010408.pdf [Accessed 09/04/2019].

UNEP. 2006. Ecosystem-based management: Markers for assessing progress. Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) of the United Nations Environment Programme (UNEP). The Hague. Available at: https://www.cbd.int/doc/meetings/mar/mcbem-2014-04/other/mcbem-2014-04-unep-01-en.pdf [Accessed 09/06/2019].

UN FAO/UNESCO. 2003. The Digital Soil Map of the World. Available from: http://www.waterbase.org/data/Global_Soil_Data/readme.pdf [Accessed 06/01/2019].

UNU-INWEH. 2019. WaterBase: World Data Grids. Available from: http://www.waterbase.org/download_data.html [Accessed: 14.12.2018].

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. & Rose, S.K. 2011. The representative concentration pathways: an overview. *Climate Change* 109: 5-31. DOI 10.1007/s10584-011-0148-z.

van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D. & Gaudillere, J.P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. How can it be assessed for vineyard management purposes?. J. Int. Sci. Vigne Vin. 43, 121–134.

Vaghefi, S.A., Abbaspour, N., Kamali, B. & Abbaspour, K.C. 2017. A toolkit for climate change analysis and pattern recognition for extreme weather conditions – Case study: California-Baja California Peninsula. *Environmental Modelling & Software.* 96: 181-198. ISSN 1364-8152. https://doi.org/10.1016/j.envsoft.2017.06.033.

VCCB. 2008. Programa Vino, Cambio Climático y Biodiversidad. Available at: http://www.vccb.cl/english/index.html [Accessed 09/06/2019].

Viñas de Colchagua, A.G. 2012. Colchagua Vina & Ruta: Colchagua Wineries. http://www.colchaguavalley.cl/en/ [Accessed 21/05/2019].

WorldClim Version2. Available at: http://worldclim.org/version2 [Accessed:11.06.2019].

World Wildlife Fund (WWF). 2019. HydroSHEDS Available from: https://www.worldwildlife.org/pages/hydrosheds [Accessed:12.12.2018].

WorldPop Project (2016). Available at: https://www.worldpop.org/ [Accessed:11.06.2019].

ANNEX 1.

Bayesian Belief Network Directed Acyclic Graph (DAG). The orange nodes represent vineyard management practices. Blue nodes represent ecosystem components/features where data can be added to explore these factors on a spatial scale. Yellow nodes highlight the key ecosystem services that can be delivered by the vineyards. Arrows or 'edges' represent the causal relationship between nodes.