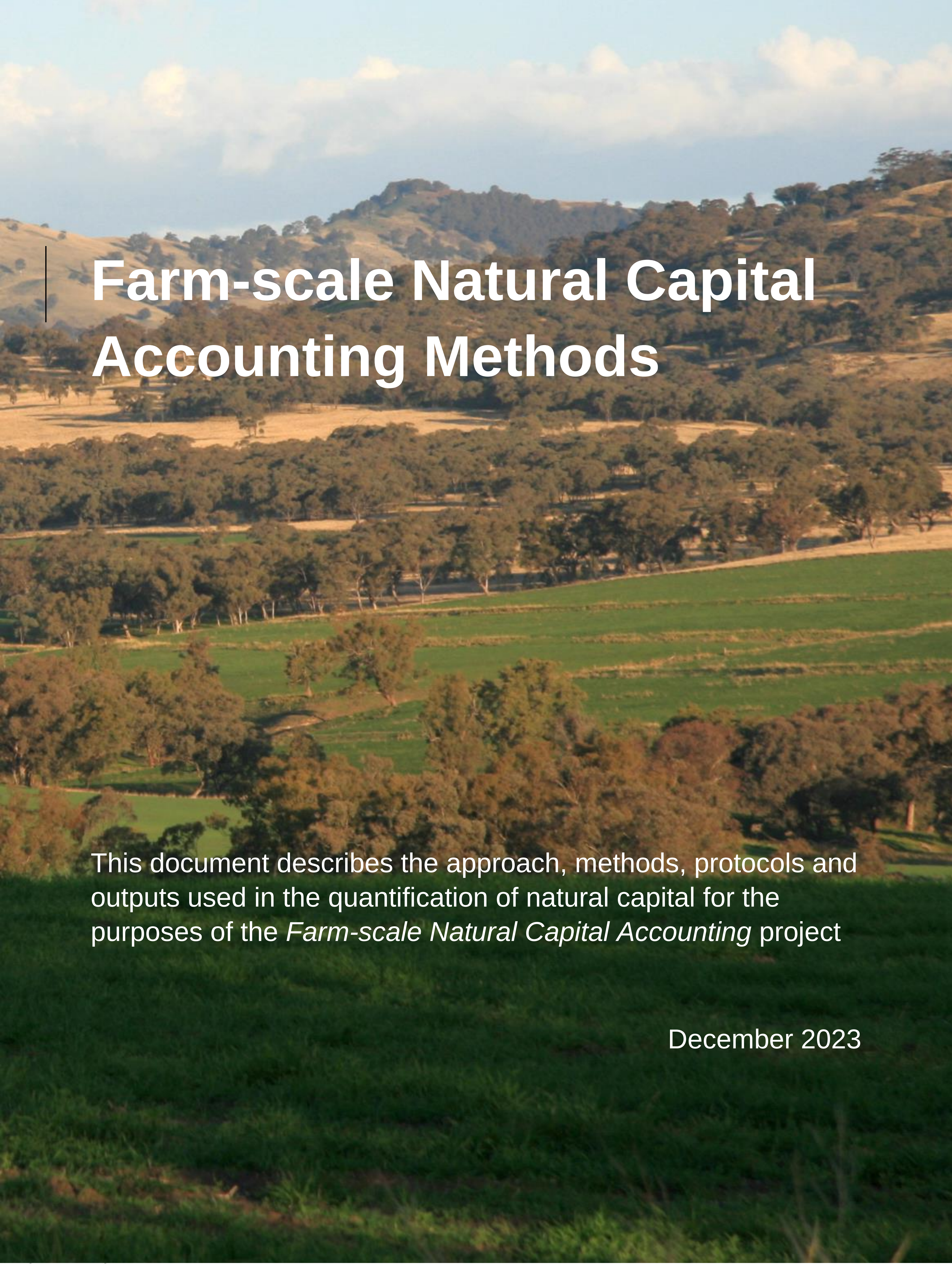

Farm-scale Natural Capital Accounting Methods

This document describes the approach, methods, protocols and outputs used in the quantification of natural capital for the purposes of the *Farm-scale Natural Capital Accounting* project

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Disclaimer

This report has been prepared for research purposes, including demonstrating how natural capital information may be compiled and presented to farmers. It does not constitute financial or investment advice and should not be relied on for this purpose. To the extent permitted by law La Trobe University accepts no responsibility for any loss, claim or liability incurred by any party in connection with this report.

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Acknowledgement of Country

We acknowledge the Traditional Custodians of Australia and their continuing connection to land and sea, waters, environment and community. We pay our respects to the Traditional Custodians of the lands on which we live and work, their culture, and their Elders past and present.

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Cover photo image credit: Alex Maisey.

Contents

Purpose of this document

There is increasing demand from the agricultural supply chain, governments and financial services providers for information about farm performance on key environmental issues relating to climate and nature risk. With support from the Commonwealth Government under its Smart Farming Partnership program, La Trobe University has been leading a consortium of partners in the *Farm-scale Natural Capital Accounting* project (hereafter FsNCA) to develop farm-scale natural capital accounts to respond to this need for farm-scale sustainability reporting and accounting. This has involved developing concepts, methods, tools and technologies for collecting, compiling and reporting on natural capital and environmental performance of individual farm businesses.

Preparation of natural capital accounts at farm scale is likely to become commonplace as farmers respond to opportunities and pressure from their supply chains to provide environmental performance information. This 'Blueprint' describes the approach used in the FsNCA for the quantification of natural capital and the preparation of farm-scale natural capital accounts. The Blueprint is organised in the following sections:

- Foundational concepts and background information
- Quantifying Natural Capital Assets
- Quantifying Biodiversity Assets
- Quantifying Ecosystem Services
- Quantifying Environmental Performance Metrics
- Quantifying Natural Capital Indices

The Blueprint is a 'roadmap' for those seeking to generate a natural capital account for a farm. The Blueprint outlines the approach, methods, protocols and data required to prepare a farm-scale account. We provide links to resources, instructions and datasets where relevant, and have included further information in the appendices. Users will require some technical expertise with GIS, running R scripts and accessing spatial datasets. The Blueprint is not intended to be a precise step by step instruction manual for generating an account because the data availability and circumstances relating to each farm will differ, which will require a degree of interpretation and modification specific to each farm. We encourage those seeking to generate an account to read the Blueprint, access the resources and adapt our approach to their circumstances.

1 Foundations and Background

1.1 State and Transition Models

The Farm-scale Natural Capital Accounting project used State and Transition Models (STM) as the underlying conceptual framework for the definition of natural capital on farms. State and Transition Models describe the typical characteristics (e.g., canopy cover, composition of ground layer, shrub density) associated with the different 'states' in which an ecosystem may persist. The state is determined by different combinations of natural or endogenous (e.g., fire, flooding, grazing) and/or human-induced or exogenous (e.g., clearing, fertilisation, livestock grazing) disturbances that affect the ecosystem. 'Transitions' between states are driven by natural disturbance regimes, deliberately imposed management interventions, by-products of other management imperatives or neglect and abandonment.

State and Transition Models have been criticised because of their low resolution, long time frames required to see transitions between states and their susceptibility to localised processes, such as weather (Sato and Lindenmayer 2021). For natural capital accounting, STMs need to be resolved enough to enable farmers and land managers to attribute transitions between condition states to management actions (Ogilvy et al. 2022) and, importantly, they need to encompass all potential ecological states observable on farms so that whole farms can be mapped. We adapted the Australian Ecosystems Models (AusEcoModels) Framework (Richards et al. 2020) and published STM for temperate grassy woodlands (Whitten et al. 2010) to generate a series of STM for each of the four major vegetation types commonly found in south-eastern Australia (woodlands, forests, grasslands, shrublands: see Appendix A). We aimed to create a generic, but high-resolution STM that can be used to describe and categorise all areas on a farm in terms of the departure from a 'reference' (best-on-offer) condition. The STM builds on previous approaches by incorporating all areas, including highly modified production ecosystems such as crops, horticulture and exotic pastures, and by adding depth to ecosystem state categories.

The STMs generated for this project include a hierarchy of classification. The 'reference' condition is considered the 'best on offer' example of the relevant vegetation biome (i.e., woodland, forest, grassland or shrubland) that has been subject to minimal human-induced disturbances. Departure from the reference condition caused by one or more exogenous disturbances will transition the ecosystem into a different 'Ecosystem Type' (e.g., Transitioning Woodland, Modified Grassland, Derived Grassland), represented by the grey boxes in the STMs (see Appendix A). Variation in the duration, severity and frequency of disturbances will influence the characteristics of the ecosystem and thus, which 'Ecosystem State' or 'Condition State' the ecosystem belongs to, represented by the white boxes in the STMs (see Appendix A).

For the purposes of natural capital accounting, we assigned all parts of the farm to a 'Ecosystem State' that summarised the characteristics of that particular area of land. The condition of this area can then be considered in the context of the purpose for which that land is primarily managed (e.g., livestock grazing, timber production, cropping or biodiversity conservation), as well as other ecosystem services it may provide, such as protection of soil, capacity to filter and purify water, and carbon sequestration and storage. Most areas of land may have multiple purposes. For example: scattered trees among native grasslands may support livestock production, conservation of biodiversity, carbon storage/sequestration and honey production and also regulate climate, water quality, and protect soil.

The assignment to a particular 'Ecosystem State' does not carry an implicit value. Value only exists in the context of the management and production goals. For example, a management goal may be to have persistent and palatable forage as well as areas for stock to shelter. These ecosystem services can be provided to a greater or lesser degree by different Ecosystem States (e.g., a less modified grassy woodland ecosystem or an exotic pasture with planted shelterbelts). The extent to which the ecosystem provides other services (e.g., habitat for biodiversity, carbon storage) may differ which may influence strategic management decisions.

The extent of different Ecosystem States on a farm was used to characterise and quantify the natural capital of the farm and to build the Ecosystem Asset Register.

1.1.1 Natural Capital as a Factor of Agricultural Production

Natural capital refers to all living and non-living elements of the natural environment that combine to provide benefits or services to people. In an agricultural context, natural capital includes both naturally occurring ecosystems (e.g., remnant native vegetation, wetlands, grasslands) and 'ecosystems' that have been established and maintained by humans that may be comprised (partly or entirely) of non-native plant species (e.g., cropland, pastures, planted vegetation). Thus, 'natural capital' does not necessarily equate to 'nativeness' or 'distance from reference condition' but rather to ecosystem assets (e.g., 'woodland', 'cropland', 'wetland', 'grassland') that have a defined spatial extent with a related set of attributes or characteristics that define their capacity to provide a range of ecosystem services.

Natural capital forms the foundation of all farming systems: soil and water support crops and pastures, plants provide food and shelter for livestock and regulate the micro-climate for crops, and native animals (e.g., insects, reptiles, birds) provide services such as pollination, pest control and waste decomposition (Figure 1). Many of the services delivered by natural capital provide direct benefits for agricultural production, either through providing resources (e.g., forage) or avoiding expenses (e.g., pest control). Other services provide public benefits, such as carbon sequestration and habitat for wildlife.

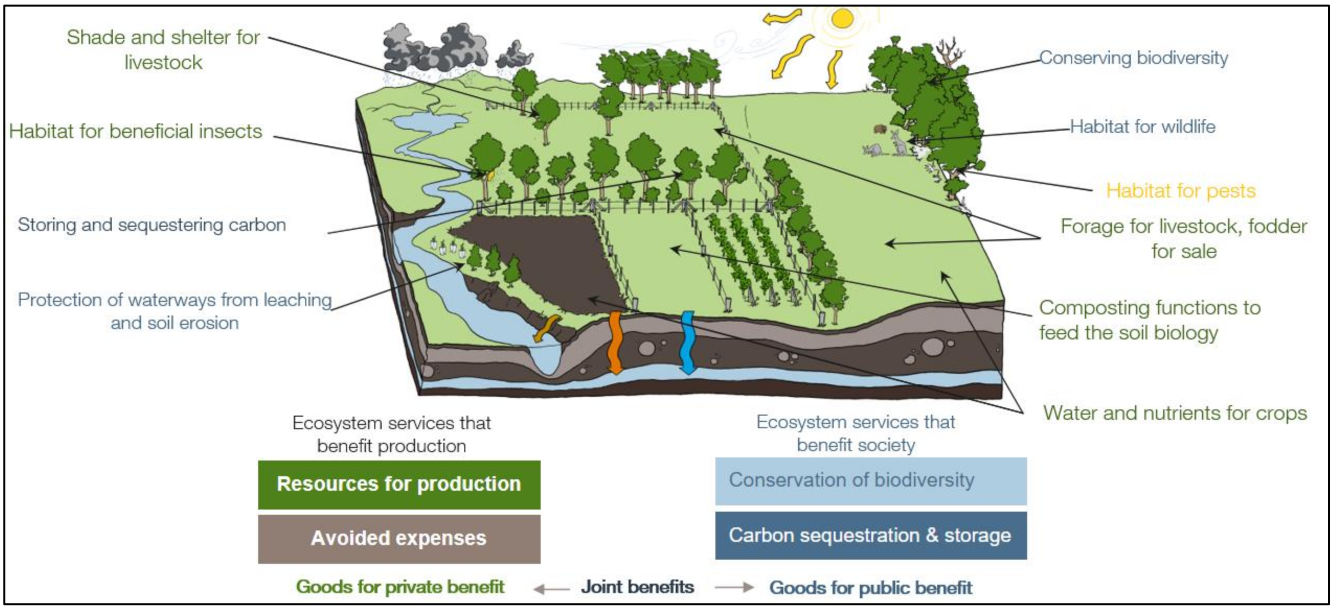

Figure 1. Ecosystem services provided by natural capital on farms.

There is broad acceptance that natural capital provides essential inputs to farming systems. Furthermore, evidence is growing that the condition or stock of natural capital is related to farm performance (Mallawaarachchi and Szakiel 2007; Sandhu et al. 2010; Ogilvy et al. 2018). This is to be expected because natural capital gives rise to a range of regulating and provisioning ecosystem services that are of direct benefit to agricultural production, and a suite of supporting and cultural ecosystem services that are of public benefit (Figure 2).

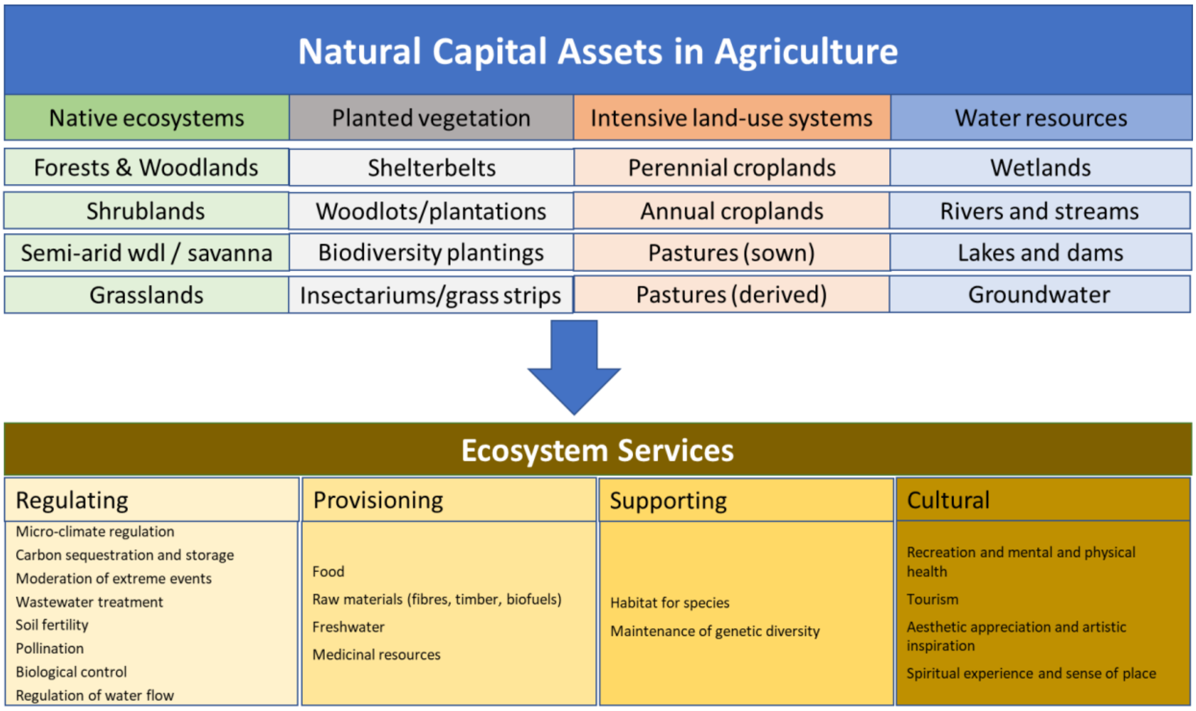

Figure 2. Diagrammatic representation of the ecosystem services (as per the UN Food and Agricultural Organisation framework) that flow from natural capital on farms.

The types and quantities of ecosystem services are governed by the types of natural capital and its condition status. In this framework, it is acknowledged that benefits to farmers and farm businesses emerge from combinations of ecological factors and human factors that work together to generate ecosystem services that are used to produce goods and services.

This document describes the methods by which information about the natural capital of a farm is collected and compiled to produce faithful representations of the various attributes of natural capital that govern the generation of economic benefits to farmers for use in producing food, fibre and other benefits for society.

1.1.2 Farm-scale Natural Capital Accounting Overview

Farm-scale Natural Capital Accounting refers to the preparation of natural capital accounts for farm businesses and integration of natural capital information with financial information (Ogilvy 2020, Ogilvy et al. 2022, O'Brien et al. 2023). Farm-scale Natural Capital Accounting leverages the concepts and standards developed in the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA) (United Nations 2021) and applies them at a paddock scale, which is the scale at which most farm natural resource management decisions are made.

Natural Capital Accounts (NCA) are composed of a series of tables that represent different components of natural capital and summarise the contribution they make to the provision of goods and services and other benefits to business and society. The foundational table is the Ecosystem Asset Register (EAR) that quantifies the area (extent) of different 'Ecosystem States' (or natural capital assets) that represent the extent and condition of natural capital on a farm at a point in time. Changes between points in time and the explanations for these are summarised in Ecosystem Accounts. Farm-scale natural capital accounts are intended to be used as input to farm management decisions, validating the results of past management actions, and highlighting opportunities for future investments to improve the ecosystem services delivered by the natural capital elements.

In this project, STMs are used as the basis for ascribing condition relative to a pre-defined 'reference state'. The choice of STMs reflects the application of the principles describing the desired qualitative characteristics of useful information in financial accounting standards. These recommend that preparers of accounts design information so that it is *material* (its inclusion or omission would affect a decision) and so that it is a *faithful representation* of what it purports to represent (it is complete, neutral and free from error). These principles are interpreted as applying in the following manner:

Material – farmer decisions about the management of agricultural ecosystems are state contingent, that is, decisions about whether they will manage an asset differently in future are based on the present state of the asset and the implications for business and personal goals. Accordingly, information about the state of an ecosystem (its type and condition) is material to the farmer.

Faithful representation – to apply the materiality principle, the information needs to faithfully represent:

- the state of the ecosystem with respect to the desired (by the farmer) ecosystem services it can generate now and into the future;
- what explains its present state; and,
- how it might be expected to respond to changes in management.

As a consequence of the application of these principles, the project designed methods to quantify the Ecosystem State (i.e., Ecosystem Type and condition) and the subsequent estimations of ecosystem services to be detailed enough to ensure a faithful representation of the landscape in sufficient detail to satisfy the materiality concept, and streamlining the complexity and effort required to generate the information so that the cost of acquisition of information does not exceed its value.

The methods summarised in this document extensively leverage work done in past natural capital accounting projects including that of Catchment Management and Natural Resource Management organisations. The methods are expected to evolve as they are used in future projects across broader landscape types. We also note that in this project, we are collecting natural capital data at single point in time, and therefore, do not produce accounts of change to natural capital over time.

2 Quantification of Natural Capital Assets

This section outlines the approach used to characterise the ecosystem (natural capital) assets of a farm, stratify those assets for the purposes of planning the on-site ecological assessment, and developing a representative sampling scheme for a farm. The stratification approach is intended to identify areas of common ecological type and condition and is based on the identified historical biome, contemporary canopy cover and long term (5 year) ground cover metrics.

2.1 Definitions

Ecosystem Type (ET): Defined by the primary land use and thresholds for Ecosystem Types in the relevant STM (e.g., Woodland, Grassland, Planted Native Trees, Exotic Woody Vegetation, Planted Native Shrubs, Crops).

Ecosystem State (ES): Defined by ecological condition thresholds representing degree of modification, as per the relevant STM.

Ecosystem Asset (EA): A single, contiguous area of the same Ecosystem State. There will commonly be multiple EAs of the same ES on a property (Figure 3).

Management Unit (MU): Discrete area subject to common management regime, usually defined by paddock fencing or a single cropped area but may also include yards, sheds, domestic and riparian areas (Figure 3).

Ecosystem Unit (EU): A contiguous area defined by a single Management Unit (typically a paddock) within an Ecosystem Asset. Thus, a single EA can be subdivided into multiple EUs by paddocks, or a single MU can be split into multiple EUs if more than one EA (Figure 3).

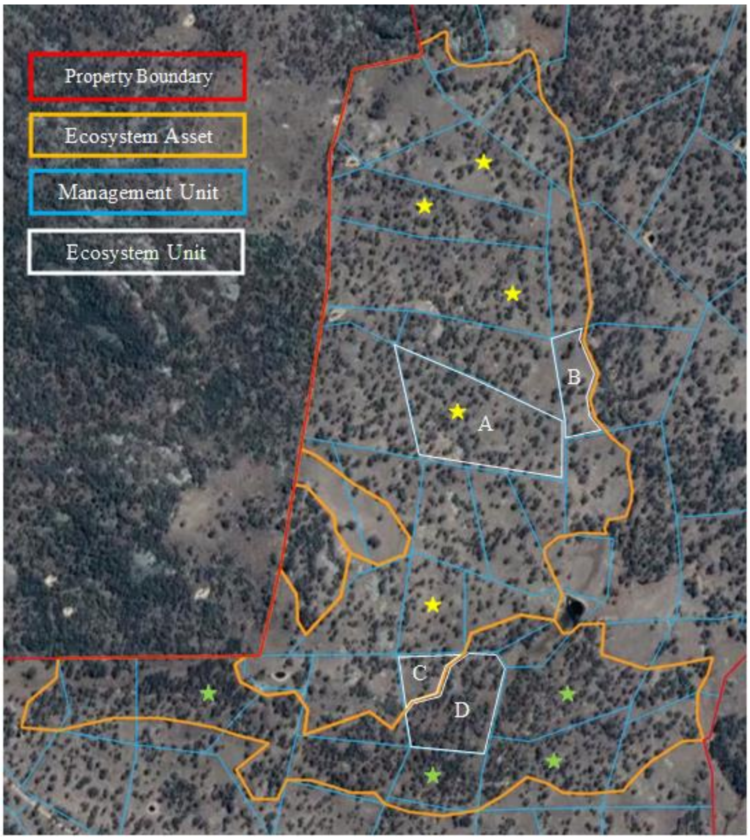

Figure 3. Relationship between Property, Ecosystem Assets, Management Units and Ecosystem Units. Ecosystem Units A and B are created by subdivision of the same Ecosystem Asset by two Management Units. Ecosystem Units C and D are created by different Ecosystem Assets occurring in the same Management Unit. Rapid ecological assessment points in different Ecosystem States are indicated by different coloured stars.

Natural Capital Accounting (NCA): The process of recording, summarising and reporting the natural capital (ecosystem assets) of a farm, changes to natural capital over time and how these relate to changes to financial income, expenditure and the performance of the farm business.

Natural Capital Indices: representations of attributes of natural capital that influence generation of ecosystem services and farm business productivity.

2.2 Overview of natural capital asset data collection

The high-level process for the natural capital asset data collection process in shown in Figure 4. It involves the following key steps:

Mapping and Remote Assessment (Section 2.3)

- Farmers provide paddock maps and using GIS software, all paddock boundaries are digitised to generate farm Management Units.
- Management data provided by farmers such as primary purpose of Management Units (i.e., production, conservation, infrastructure), age and composition of any tree plantings, current crop rotations, fertiliser history and grazing management is compiled.
- Remote sensed data is used to generate ecological overlays and identify Management Units with similar contemporary canopy cover and ground cover characteristics.
- Using the farm management data, ecological overlays and paddock boundaries, the farm is classified into Ecosystem Units - areas of putatively similar ecological condition (i.e., potentially representing Ecosystem States) within a single Management Unit.

Field Observations (Section 2.4)

- A representative sampling strategy is devised to allocate rapid ecological assessment (REA) points across all the putative Ecosystem States present on the farm.
- A qualified ecologist conducts a REA at each of the assessment points. This includes assigning an Ecosystem State to each Ecosystem Unit visited, as per the thresholds in the STM framework.

Validation and Imputation (Section 2.4.1)

- The REA data and the field-validated Ecosystem State are used to assign an Ecosystem State to visited Ecosystem Units.
- The farm management information and the ecological overlays are then used to impute (assign by inference) the Ecosystem State to the remainder of the farm's (unvisited) Ecosystem Units.
- The Ecosystem States are checked by the farmer for gross errors or misclassifications.

Compile Asset Register (Section 2.6)

- The validated Ecosystem States are entered into the Ecosystem Asset Register (EAR), which is a table listing all Ecosystem Units, and their Ecosystem State, area, primary and secondary purpose, and any relevant farm management information.

Generate Accounts (Section 2.7)

- The EAR is used to compile the Natural Capital Asset account, which summarises the extent of each Ecosystem State (i.e., condition state) on the farm.

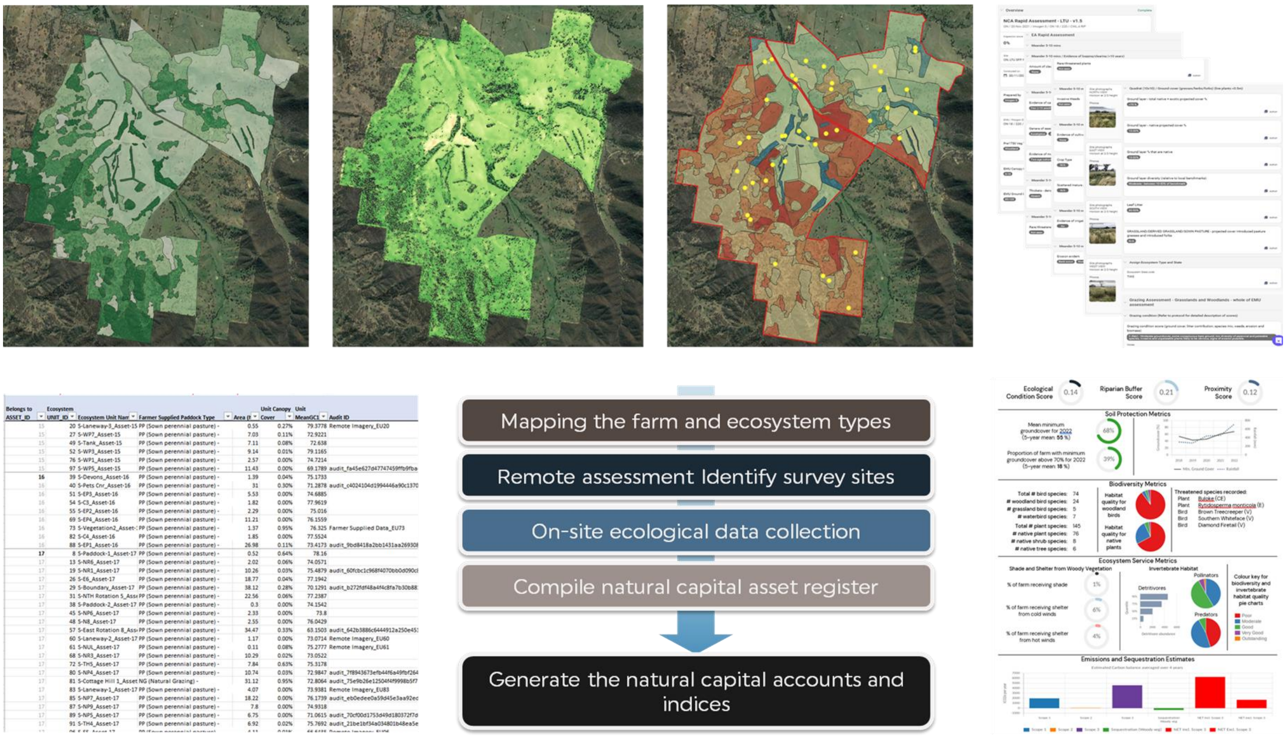

Figure 4. Overview of natural capital asset data compilation to generate farm-scale natural capital accounts.

2.3 Mapping Management Units, Ecosystem Units and Ecosystem Assets

2.3.1 Management Units

The Management Units (paddocks) are provided by the farmer. This can be in the form of a hand drawn map, overlays on an aerial photo, data exported from farm management software or layers exported from GIS software. Depending on the format in which these are provided, these can be either directly imported into GIS software or may need to be manually digitised using GIS software.

Where possible, the farmer also provides information about the management applied to each paddock assisted by a numbered farm paddock map. Information may include details of tree plantings (year of planting, composition, purpose), current/historical crop rotations and fertiliser use, grazing management, primary production purpose (grazing, cropping, forestry, horticulture) and areas excluded from production (e.g., riparian zones and biodiversity conservation areas). This information is used to identify areas under similar management and to inform classification of Ecosystem States.

The final output is a GIS layer of the Management Units on a farm, that largely corresponds to paddocks and any substantive variation in management that may occur at a sub-paddock level.

2.3.2 Ecosystem Units

Three ecological overlays are used to define and describe the Ecosystem Units: pre-1750 vegetation type, canopy cover and ground cover.

2.3.2.1 Step 1: Canopy Cover

We used Picterra© (https://picterra.ch), a commercial image-based machine learning platform to identify areas (polygons) with similar tree canopy cover (different machine learning platforms or algorithms could be used to generate the polygons). To do this, farm imagery (ESRI World Maps) was loaded into the Picterra platform, and we trained seven individual algorithms (detectors) to identify contiguous areas belonging to one of seven canopy cover density classes: 0-1%, 1-5%, 5-15%, 15-30%, 30-50%, 50-100%, and tree lanes (very narrow strips of trees, generally <10m wide). The canopy cover classes correspond to different Ecosystem States in our STM framework. The resulting seven vector layers were then merged to generate a single vector layer. The final output is a 'Canopy Cover' GIS layer with each polygon being assigned to a mutually-exclusive canopy cover class (Figure 5).

2.3.2.2 Step 2: Ecosystem Units – first iteration

The Canopy Cover layer was then intersected with the Management Unit layer to generate the first iteration of the Ecosystem Units. An estimate of canopy cover was then calculated for each EU using a tree mask raster (generated via Picterra or manually created from the ESRI image, based on red/blue/green band ratios). The final output is a GIS layer of the Ecosystem Units on a farm, with each EU (polygon) attributed by a canopy cover class.

2.3.2.3 Step 3: Ecosystem Units – Ground Cover

The next step is to generate ground cover metrics for the farm as a whole and apply those to the Ecosystem Unit polygons. The base data for this analysis is sourced from the Fractional Cover 25m Percentiles 2.2.1 product from Digital Earth Australia (Lymburner 2021). An annual raster dataset was generated for each of the preceding 5 years to represent the 10^{th} percentile ground cover (calculated as 100 – 90^{th} Percentile Bare Soil dataset), and then a mean annual 10^{th} percentile groundcover raster (MEANGC10) was generated as temporal mean across the 5 years.

A spatial mean of each of the MEANGC10 was then calculated for all pixels within each Ecosystem Unit polygon. Each Ecosystem Unit was then assigned to a ground cover class based on quintiles of the MEANGC10 metric (0-20, 20-40, 40-60, 60-80 and 80-100). The final output is an updated GIS layer of the Ecosystem Units on a farm, with each EU (polygon) attributed by a ground cover class, a canopy cover class.

2.3.2.4 Step 4: Ecosystem Units – Biome

The updated Ecosystem Unit layer is then overlayed with the pre-1750 vegetation type (NVIS major vegetation group) to determine the pre-development 'biome' to which that Ecosystem Unit belongs. We concatenated the NVIS major vegetation groups to four biomes: forest, woodland, grassland and shrubland, and then selected the dominant pre-1750 vegetation type for each Ecosystem Unit. The final output is a GIS layer with each Ecosystem Unit assigned to a combined class based on the pre-1750 biome, canopy cover class, and ground cover class (Figure 6).

2.3.3 Ecosystem Assets

The Ecosystem Asset layer is then produced by merging adjacent Ecosystem Units of the same combined class. The canopy cover and ground cover metrics are then recalculated for each EA.

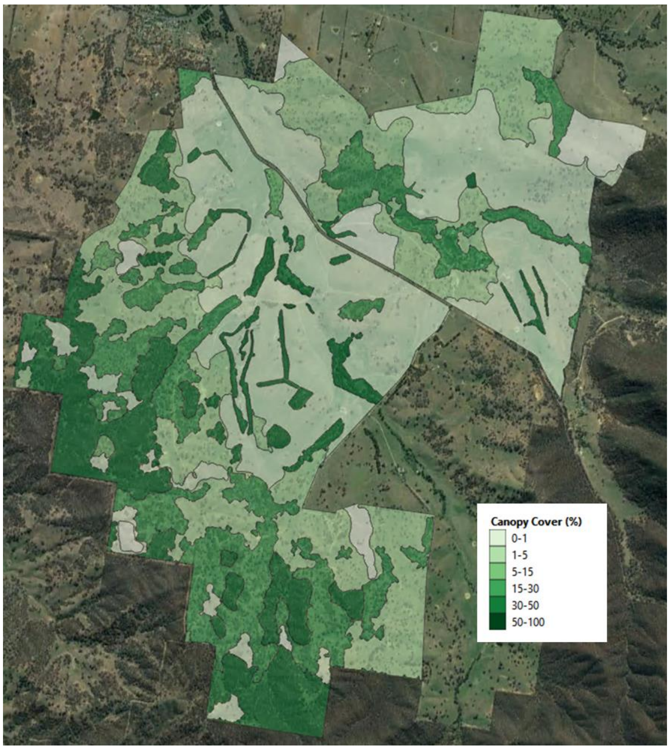

Figure 5. Example of ecological overlay with canopy classification.

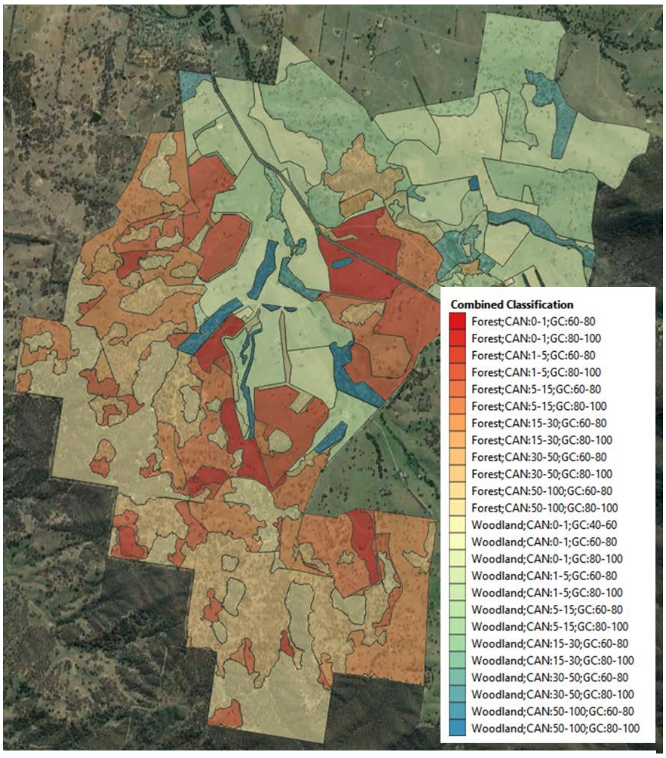

Figure 6. Combined classification of ecosystem units for a farm.

2.4 Field observations

We used the Ecosystem Asset combined class to identify (from remote sensed data and imagery) areas that have similar canopy cover and ground cover characteristics. The purpose of the on-ground Rapid Ecological Assessments is to empirically assess (or ground-truth) the similarity of the land condition, vegetation structure and floristic composition of Ecosystem Assets/Units within the same combined class. The field ecologist also assigns an Ecosystem State (from the relevant STM) and forage class (see below) to each Ecosystem Unit assessed. This data is then used to confirm whether Ecosystem Units/Assets in the same combined class correspond to a particular Ecosystem State, and where there is variation within a category of the combined class, to identify potential sources of that variation (e.g., management, topography, soil type). This is then used to impute the Ecosystem State of Ecosystem Units that were not assessed on the ground.

2.4.1 Representative stratified sampling strategy

The aim of the representative sampling strategy is to assess all the Ecosystem Asset combined classes (i.e., primary level of stratification) that occur on a farm roughly in proportion to their relative extent. The number and location of the Rapid Ecological Assessment points is determined prior to going into the field by the following steps.

2.4.1.1 Step 1 – Number of assessment points per combined class of the Ecosystem Asset layer

The number of assessment points per Ecosystem Asset combined class is primarily based on the total area of the class on the farm as per Table 1. The reliability of imputation will also depend on the variability (e.g., topography, vegetation, management) within a class, so the number of points per class may be varied depending on the variability within each class on the farm (Table 1). In planning, the number of points per class is based on the 'high variability' category, then, after the random meander (see below), the ecologist will decide if fewer sites will suffice (i.e., lower variability).

Table 1: Target number of Rapid Assessment Points as a function of area and variability of each Ecosystem Asset combined class present on a farm.

Area of Ecosystem Asset combined class	High Variability	Moderate variability	Low variability
<5 ha	2	1	1
>5 and ≤20 ha	3	2	2
>20 and ≤50 ha	4	3	2
>50 and ≤100 ha	5	4	3
>100 and ≤200 ha	6	5	4
>200 and ≤500 ha	7	6	4
>500 and <1000 ha	8	7	5
>1000 ha	10	8	6

Therefore, the theoretical or ideal number of assessment points per farm will be determined the size and complexity (number of combined classes) of the farm. However, in reality, the total number of assessment points per farm will be a trade-off between the size and complexity of the farm, and the practical constraints of completing the field assessments within the time available (typically two days). When practical or logistical constraints mean that fewer than the target number of points per combined class can be surveyed, remove sites from the classes that have the highest sampling representation (as a proportion of the recommended number) until the desired number of survey sites is reached.

2.4.1.2 Step 2 – Selecting Ecosystem Assets

Where there are multiple Ecosystem Assets per Ecosystem Asset combined class (likely on most properties), the following rules are used to determine which (and how many) Ecosystem Assets are assessed until the allocated number of points per combined class (Table 1) is exhausted.

a) Include the largest Ecosystem Asset per Ecosystem Asset combined class.
b) Include extremes in topographic variation. For example, where significant altitudinal variation exists within a combined class, assess Ecosystem Assets that represent the lowest and highest altitude of the combined class.
c) Where possible, include Ecosystem Assets in geographically distant parts of the property (e.g., north/south or east/west of property).
d) Where there is substantial variation in ground cover within an Ecosystem Asset combined class, include Ecosystem Assets that span the variation.
e) Include riparian zones when they are located within an Ecosystem Asset combined class. Additional information is gathered about the condition of riparian areas.
f) Where paddock management details are available from the farmer, include sites in each of the classes of paddocks (e.g. long-term pastures, annual pastures, crops, different pasture types)

2.4.1.3 *Step 3 – Number of assessment points per Ecosystem Asset*

In general, larger and more variable Ecosystem Assets should be allocated more assessment points but with flexibility to allocate assessment points across multiple Ecosystem Assets within a combined class to accommodate the rules in Step 2. For example, if the combined class is comprised of only one or two Ecosystem Assets, the assessment points may be allocated between the Ecosystem Assets in proportion to area, as long as the other rules are also met. In other circumstances, points may need to be skewed (i.e., not proportional to area) to ensure other rules are met. The key point is that there are enough assessment points within each Ecosystem Asset such that the ecologist has confidence that the Ecosystem Asset has a fair assessment.

2.4.1.4 *Step 4 – Location of assessment points within Ecosystem Assets*

Assessment points should be located in an area with a 5-year mean 10th percentile ground cover that approximates the mean value of the whole Ecosystem Unit (i.e., it is representative; Fig. 7). Assessment points must also be accessible (ideally, no further than 200 m from a track/road) and located at least 200 m apart when there are multiple points in the same Ecosystem Asset. Within these constraints, assessment points should be randomly located within an Ecosystem Unit.

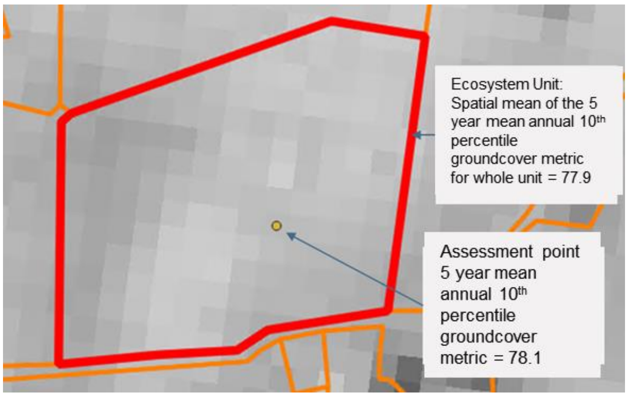

Figure 7. Alignment of mean ground cover between the Ecosystem Unit and the assessment point.

Figure 8 provides an example of the sites selected for field observations.

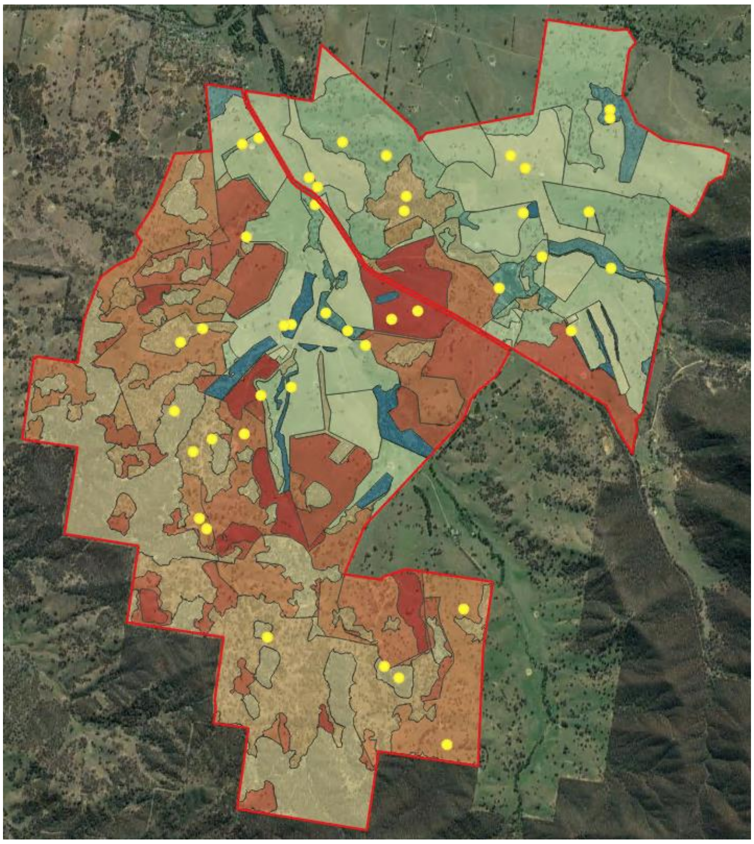

Figure 8. Example of farm map showing assessment points selected for field observations. Yellow dots indicate the location of field observation. Each site is allocated a unique identifier for curation of data for analysis and future reference.

2.4.2 Rapid Ecological Assessments

This section summarises the key considerations of the NCA rapid ecological assessment. The full standard operating procedure is provided in Appendix B.

The rapid ecological assessment is conducted at the scale of the Ecosystem Unit. This will usually be a single paddock but sometimes a paddock may contain multiple Ecosystem Assets or Management Units. In that case, only that part of the paddock that relates to the Ecosystem Unit in which the assessment point is placed is assessed. The objectives of the rapid ecological assessment are:

- to assess whether the Ecosystem Unit is relatively uniform in its ecological condition;
- to assess whether the Ecosystem Unit is representative of its parent Ecosystem Asset;
- to assess the ecological condition of the Ecosystem Unit;
- to assess the pasture classification (for grazed land) of the Ecosystem Unit;
- to assess the soil condition (for cropping land) of the Ecosystem Uni; and
- to assign an Ecosystem State (condition) to the Ecosystem Unit.

The rapid ecological assessment uses a multi-scale approach for data collection. The type of information captured at each scale is summarised below:

2.4.2.1 Whole of Ecosystem Unit

The assessor conducts a 'meander' (i.e., an unstructured walk to inspect different parts of the Ecosystem Unit) through the Ecosystem Unit for approximately 5 to 10 mins. A key purpose of the meander is to assess the overall uniformity (consistency) of the Ecosystem Unit in terms of canopy cover and composition, shrub cover, and ground layer cover and composition. If there is substantial variability (i.e., clearly more than one Ecosystem State present in the Ecosystem Unit), the approximate boundaries of the different states and the source of the variation (e.g., topography, management) are noted. During the meander, the assessor also collects qualitative or semi-quantitative information on:

1. tree canopy layer – number of species present, number of age cohorts, health (e.g., dieback, fire), hollow-bearing trees, recent clearing/logging, recruitment, and presence of thickets (dense seedling regrowth)
2. weeds – note any weeds of national significance or other notable weeds
3. cropping – types of crops sown (if any)
4. irrigation – evidence of irrigation infrastructure
5. coarse woody debris

2.4.2.2 1-ha Plot

In an estimated 1-ha plot (i.e., 55-m radius circle or 100m x 100m) centred on the assessment point, the following attributes are assessed:

1. tree canopy crown cover
2. type and approximate age of any planted trees and shrubs
3. cover and diversity of native and exotic shrubs
4. cover and diversity of ground layer plants
5. presence and type of erosion
6. photographs in each cardinal direction are also taken

2.4.2.3 Assessment points

Within an estimated 20 m X 60 m quadrat based on the assessment point, between 3 to 5 rapid assessments are made within a 2 m radius circle. These include assessment of:

1. density (cover) and height of 5 most dominant plant species
2. overall cover of herbaceous plants
3. litter cover

The information from the meander, 1-ha plot and assessment points is used to assign the Ecosystem Unit to an Ecosystem Type and Ecosystem State in the field. It is useful to have the Ecosystem State definitions and thresholds (see Appendix A) and a decision-tree (available upon request) available in the field to assist the classification. The information from the 1-ha plot and assessment points is used in the assessment of pasture classification (see 4.3.3) as well as ecological condition.

2.4.2.4 Riparian assessment

At riparian sites, additional data is collected relating to stock management, streambank erosion, width of riparian canopy cover, width of riparian shrub cover.

2.4.2.5 Soil condition

The assessment of soil condition is designed to provide the farmer with information to track long-term trends in soil condition and thus, the capacity of the Ecosystem Unit to support agricultural production over the long-term without reliance on ongoing inputs. This assessment is not intended to replace or inform agronomic assessments of inputs required for short-term production outcomes (e.g., fertiliser, lime, micro-nutrient, organic amendments).

The soil condition assessment is prioritised for cropping sites where vegetation is predominantly cultivated annuals. For perennial vegetation, one soil condition assessment is assigned per canopy cover category. The soil condition assessment is modified from Shepherd (2009) and the North Central CMA (2016) visual soil assessment methods. Close to the designated assessment point, the assessor digs a 30 cm deep hole to expose the soil profile and topsoil depth. Soil samples are collected from the topsoil and subsoil for later analysis. The following attributes are assessed (either in the field or from the samples):

- topsoil depth (assessed by change in colour)
- porosity
- compaction (using a penetrometer)
- pH
- texture
- slaking and dispersion

2.4.2.6 Equipment required for Rapid Ecological Assessments

Field observations require the following tools:

- Phone or tablet with digital navigation mapping (e.g., Avenza, Gaia or similar) and survey data capture (e.g., Fulcrum, iAuditor or similar) apps.
- A geocoded farm map showing the location of pre-determined assessment points (Figure 8).

- Printed maps of the farm for navigation and noting general farm management observations.
- Flowchart (decision tree) and thresholds for assignment of Ecosystem State.
- Soil condition assessment equipment – spade, penetrometer, paper bags (for soil samples), visual guides, tape measure/ruler, pH meter (for in-field measurements, optional).

2.5 Validation and Imputation

The data from the rapid ecological assessments is compiled into databases or spreadsheets. This data is then combined with the STMs to assign an Ecosystem Type, Ecosystem State and pasture classification (for grazed land) to every Ecosystem Unit on the property. Where an Ecosystem Unit has been visited, the metrics from the field visit are used to automatically determine the Ecosystem State. The automated Ecosystem State assignment is reviewed by the ecologist, and expert judgement is applied to confirm (or update) the assigned state. Justification for any overrides is included in the imputation spreadsheet.

For Ecosystem Units that were not visited/assessed, we draw heavily on the strategy used by the Australian Bureau of Statistics of using imputations to describe populations and the economy. That is, we impute (assign by inference) the Ecosystem State for unvisited Ecosystem Units based on the information gained from the field observations.

The process for imputing the state for unvisited sites is a manual process which leverages the ecologist's expert knowledge of the landscape. Each unvisited ecosystem unit is linked to one of the rapid assessments based on a combination of factors, including:

- Canopy cover and ground cover metrics (matching those of the rapid assessment point)
- Location within the farm (where possible, points close to the EU are used to impute condition)
- Farm management information (supplied by the farmer) – this could include classification of the pasture age and type, as well as planting information (age, species mix) for tree lanes and planted vegetation
- Aspect and slope
- Other queues from the spatial imagery

Where there is reason to believe a different Ecosystem State is appropriate (e.g., farmer-supplied information, spatial imagery), the assessor has the discretion to make this change.

A log of the rule or rationale used to impute the Ecosystem State is recorded against each Ecosystem Unit to ensure traceability as part of the reporting process. This information is presented as part of the accounts (Appendix C). The imputation log is designed to make clear which parts of the farm have been directly observed and which have had their Ecosystem State imputed, and which Ecosystem Units were used to assign their Ecosystem State. Users of the accounts can then decide how they wish to use this information.

A map of the field-assigned and imputed Ecosystem States and the imputation log is then sent to the farmer for checking. Any gross errors or misclassifications are updated and the final, validated Ecosystem States applied to all Ecosystem Units and Ecosystem Assets.

2.6 Compile Asset Register

The validated Ecosystem Units are compiled into the Ecosystem Asset Register (EAR), which is a table listing all Ecosystem Units, and their Ecosystem Asset, Ecosystem Type, Ecosystem State, area, primary purpose, grazing classification and any relevant farm management information.

2.7 Generate Natural Capital Asset Accounts

The Ecosystem Asset Register is used to compile the Natural Capital Asset account, which summarises the extent (area) of each Ecosystem State (i.e., condition state) on the farm (Table 2).

Table 2. Example of Natural Capital Asset account. Ecosystem Type and State on Orana Park by extent (ha) as @ 18/10/2021.

Ecosystem Type	Ecosystem State	Area (ha)	Proportion of farm
Horticulture	Perennial Horticulture	1219.18	23 %
Woodland	Transitioning Woodland 1	154.94	3 %
Woodland	Transitioning Woodland 3	40.64	1 %
Woodland	Transitioning Woodland 4	58.74	1 %
Grassland	Derived Grassland 1	157.02	3 %
Grassland	Modified Grassland 5	87.79	2 %
Cropland	Non-irrigated crop with scattered trees	170.74	3 %
Cropland	Non-irrigated crop - no trees	2496.96	48 %
Cropland	Irrigated crop	671.10	13 %
Planted vegetation	Planted native trees - maturing (10-40 years)	10.15	0 %
Infrastructure	Domestic Infrastructure	25.37	0 %
Infrastructure	Roads & Laneways	135.31	3 %
Infrastructure	Sheds & Yards	2.13	0 %
Infrastructure	Water infrastructure (dams, channels)	20.86	0 %
Total		**5,250.93**	**100%**

3 Quantification of Biodiversity Assets

This section outlines how the accounts of the biodiversity assets were generated for each farm. The accounts provide information about the extent and quality of habitat on the farm for birds and plants. Further research is required to extend the accounts to other taxonomic groups, such as reptiles, bats, arboreal mammals, frogs or groups of invertebrates (e.g., butterflies) (but see Section 4 for invertebrate functional groups).

We modelled the species richness of birds and plants to give an indication of the value of the farm for biodiversity conservation. Our spatially explicit models enable us to generate maps that indicate where on the farm the biodiversity assets are higher or lower for different groups of birds and plants. The maps in the accounts show the predicted species richness (i.e., number of species) per hectare for birds and per 0.05 ha for plants across the farm. They are derived from statistical models that used Ecosystem State, topography, the size of the habitat patch and counts of species at sites to predict bird and plant species richness across the farm. The models were based on data collected from 1155 sites (from 50 farms) for birds and 1090 sites (from 48 farms) for plants on farms across south-eastern Australia (see Appendix E).

3.1 Bird and plant groups

To better understand the distribution of bird and plant diversity in relation to natural capital assets, we grouped species based on either their broad habitat preference (for birds) or their life form (for plants) (Table 3) and modelled the species richness of each group separately. Other groups of interest could be modelled in future accounts.

Table 3. Habitat groups for bird and plant species used in the biodiversity accounts.

Group	Description
Birds	
All bird species	All bird species recorded regardless of habitat preference.
Woodland birds	Bird species that depend on woodland/forests for all daily activities – foraging, roosting, nesting. This group is experiencing population declines and is of conservation significance.
Grassland birds	Birds that rely on grassland habitats for their daily activity.
Plants	
All plants	All native and exotic plant species recorded regardless of life form.
All native plants	All native plant species recorded regardless of life form.
Native shrubs	Woody or herbaceous native shrubs generally between 1-5 m high with a branching form.
Native ground layer	Native plants less than about 1 m high. This group includes grasses, forbs, graminoids (sedges and rushes) and climbers.

3.2 Explanatory variables

We considered a wide range of explanatory variables in the model building process (Table 4).

The Ecosystem State variable was generated by combining structurally and compositionally similar states from the STMs for woodlands, forests, grasslands and shrublands (Table 5).

To calculate Patch Size, the Ecosystem Asset polygons for each farm were dissolved by broad Ecosystem Type in QGIS version 3.18. This created spatial layers with polygons that represented patches of similar habitat type (i.e., woodland, grassland, crop, etc.). The area of each polygon was then calculated in QGIS, and the layer converted to a raster and values (patch size) were extracted for each site. For Woodland Patch Size, these steps were repeated, but all non-woodland patches were assigned an area of 0 ha before the polygon layer was converted to raster. To reduce the influence of outliers, values were $\log_{10}$-transformed prior to analysis.

To calculate Elevation for each site, we used a 1-second Digital Elevation Model (DEM) for Australia (Gallant et al. 2011). Values were extracted for each site using the raster package in R.

To calculate the vertical Height Above the Nearest Drainage (HAND), we used a DEM (Renno et al. 2008) and followed the protocol outlined in https://www.youtube.com/watch?v=CtBiwxiv-Fg. A raster of HAND was generated for each farm using the PCRaster Tool plugin in QGIS. Values were extracted for each site using the raster package in R. Elevation could be used as a substitute for HAND if necessary.

3.3 Modelling procedure

We used a model selection approach (explanatory variables responsible for a significant increase in model deviance explained were retained in the model) to determine which explanatory variables to include in the final model for each group (Table 4). We used generalised additive models (GAM) to relate the diversity of each group of birds and plants to Ecosystem State. GAMs were used for two reasons: 1) relationships between diversity and covariates were expected to be non-linear, and 2) random effects can be included in GAMs as a random spline, akin to random terms in a mixed model framework, while allowing for straight forward calculations of deviance explained (Wood 2017). To account for potential spatial autocorrelation and unknown influence of individual farming practices, farm ID was included as a random spline during the model building process. To predict bird and plant species richness on new farms, this variable should be removed from the model and replaced with the bioregion variable. GAMs were built using the mgcv package in R.

Table 4. Candidate explanatory variables included in models to explain the diversity of birds and plants. The models in which each variable was included is also indicated.

Variable	Variable code	Scale	Unit	Description	Models that included the variable
Ecosystem state	Eco.State.3	Patch	Category	A categorical variable based on the ecosystem states defined in the state-and-transition models. For spatial predictions, categories were assigned numeric values that correspond to the raster layers for each farm.	All models
Woodland patch size	WoodyPatchArea Log	Patch	ha(log)	Area of contiguous woodland connected to the survey site. 'Woodland' includes remnant and planted native woodlands. Log-transformed	Woodland birds
Patch size (log)	PatchAreaLog	Patch	ha(log)	Area of contiguous habitat connected to the survey site. Log-transformed.	All birds, Grassland birds, All native plants, Native shrubs, Native ground layer
Elevation	Elevation	Site	m	Height above sea level. Derived from digital elevation model.	Woodland birds, Grassland birds, All plants, All native plants, Native ground layer
Height above nearest drainage	HAND	Site	m	Vertical height above the nearest named drainage system. Derived from a digital elevation model.	All birds, All plants
Geographic state	GeogState2	Region	Category	A categorical variable with 2 levels to account for the difference in total species pool between mainland Australia and Tasmania.	Grassland birds
Bioregion	Bioregion2	Region	Category	A categorical variable with 6 levels to account for the influence of bioregion. Bioregions include: Central Victoria, Liverpool Plains, New England Tablelands, NSW Inland Slopes, Tasmania, Wimmera.	All birds, Woodland birds

Table 5. Ecosystem state categories that were included in the ecosystem state variable.

Ecosystem state code	Description	States included from STMs
RW	Native woodland or forest with very high diversity relative to local benchmarks. No exotic species. 'Best on offer'.	RW, RF
TW1	Woodland or forest (canopy cover 15 – 70%) with high native diversity. Few exotic species.	TW1, TF1, DF1
TW2	Woodland or forest (canopy cover 15 – 70%) with mostly native understorey. Some exotic species.	TW2, TF2, DF2
TW3	Woodland or forest (canopy cover 5 – 70%) with mostly exotic understorey.	TW3, TF3, DF3
TW4	Woodland or forest (canopy cover 5 – 50%) with entirely exotic understorey.	TW4, TF4, DF4
TW5	Dense thicket of regenerating canopy trees. Often patchily distributed around mature trees.	TW5, TF5, DF5, TW6, TF6, DF6
RGt	Reference grassland with scattered trees. Very high diversity. 'Best on offer'.	RGt
DG1t	Derived native grassland with scattered trees. High native diversity and few exotic species.	DG1t, MG1t
DG2t	Derived mixed grassland with scattered trees. Mostly native with some exotic species.	DG2t, MG2t
DG3t	Derived grassland with scattered trees. Mostly exotic with few native species.	DG3t, MG3t
DG4t	Derived exotic grassland with scattered trees. Very few native species.	DG4t, MG4t
DG5t	Derived entirely exotic grassland with scattered trees.	DG5t, MG5t, DG6t, MG6t
RG	Reference grassland. Very high diversity. 'Best on offer'.	RG
DG1	Derived native grassland with high diversity and few exotic species.	DG1, MG1
DG2	Derived mixed grassland, mostly native with some exotic species.	DG2, MG2
DG3	Derived grassland, mostly exotic with few native species.	DG3, MG3
DG4	Derived exotic grassland with very few native species.	DG4, MG4
DG5	Derived entirely exotic grassland.	DG5, MG5, DG6, MG6
DS1	Native shrubland (shrub cover >10%) with mostly native ground layer.	DS1, DS2, TS1, TS2
DS3	Native shrubland (shrub cover >10%) with mostly exotic ground layer.	DS3, DS4, TS3, TS4
PNT1	Planted native trees 0 – 10 years.	PNT1
PNT2	Planted native trees 11 – 40 years.	PNT2
PNT3	Planted native trees >40 years.	PNT3
PNS2	Planted native shrubs >3 years.	PNS2
EWV1	Exotic trees. Canopy cover >5%.	EWV1
EWV2	Exotic shrubland. Canopy cover <5%. Shrub cover >10%.	EWV2
EWV3	Perennial horticulture (olive groves).	EWV3
C1	Crops with scattered trees.	C1
C2	Crops without scattered trees.	C2, C3

(Section 3.3 Modelling Procedures continued)

To generate accounts of bird and plant habitat quality, raster layers of each of the explanatory variables described in Table 1 are needed at a resolution of 10 x 10 m. These variables are then entered into the model equations below to generate spatial predictions of species richness. A variable to account for the influence of bioregion on bird and plant diversity should be included for farms within the same bioregions as the original Natural Capital Accounting project (i.e., bioregions covered by Central Victoria, Liverpool Plains, New England Tablelands, NSW Inland Slopes, Tasmania, Wimmera).

The model equations used to generate biodiversity accounts for farms in R language are:

All bird species richness ~ Eco.State.3 + s(PatchAreaLog, k=3) + s(HAND) + Bioregion2, family = Poisson, data = [data frame]

Woodland bird species richness ~ Eco.State.3 + s(WoodyPatchAreaLog, k=3) + s(Elevation, k=3) + Bioregion2, family = Poisson, data = [data frame]

Grassland bird species richness ~ Eco.State.3 + s(PatchAreaLog, K=3) + s(Elevation, K=3) + Bioregion2, family = Poisson, data = [data frame]

All plant species richness ~ Eco.State.3 + s(HAND, k=3) + s(Elevation, k=3) + Bioregion2, family = Poisson, data = [data frame]

All native plants species richness ~ Eco.State.3 + s(Elevation, k=3) + s(PatchAreaLog, k=3) + Bioregion2, family = Poisson, data = [data frame]

Native ground layer species richness ~ Eco.State.3 + s(Elevation, k=3) + s(PatchAreaLog, k=3) + Bioregion2, family = Poisson, data = [data frame]

Native shrub species richness ~ Eco.State.3 + s(PatchAreaLog, k=3) + Bioregion2, family = Poisson, data = [data frame]

The models are stored as RDA files that can be loaded in R and used to predict to new farms within the bioregions of the 50 NCA project farms without access to the original data base. If the farm is located outside the bioregions represented in our original dataset, the bioregion variable should be dropped. This will reduce the predictive power of the models but will enable predictions to new areas. The RDA files are available upon request from the La Trobe project team.

3.4 Generating a biodiversity account

To convert the models of species richness into a biodiversity account, we generated spatial predictions (i.e., maps) of species richness for each group of birds and plants (Figure 9). These spatially explicit models indicate areas on the farm that are expected to support more, or fewer, species of each group. Spatial predictions were generated using the Raster package in R.

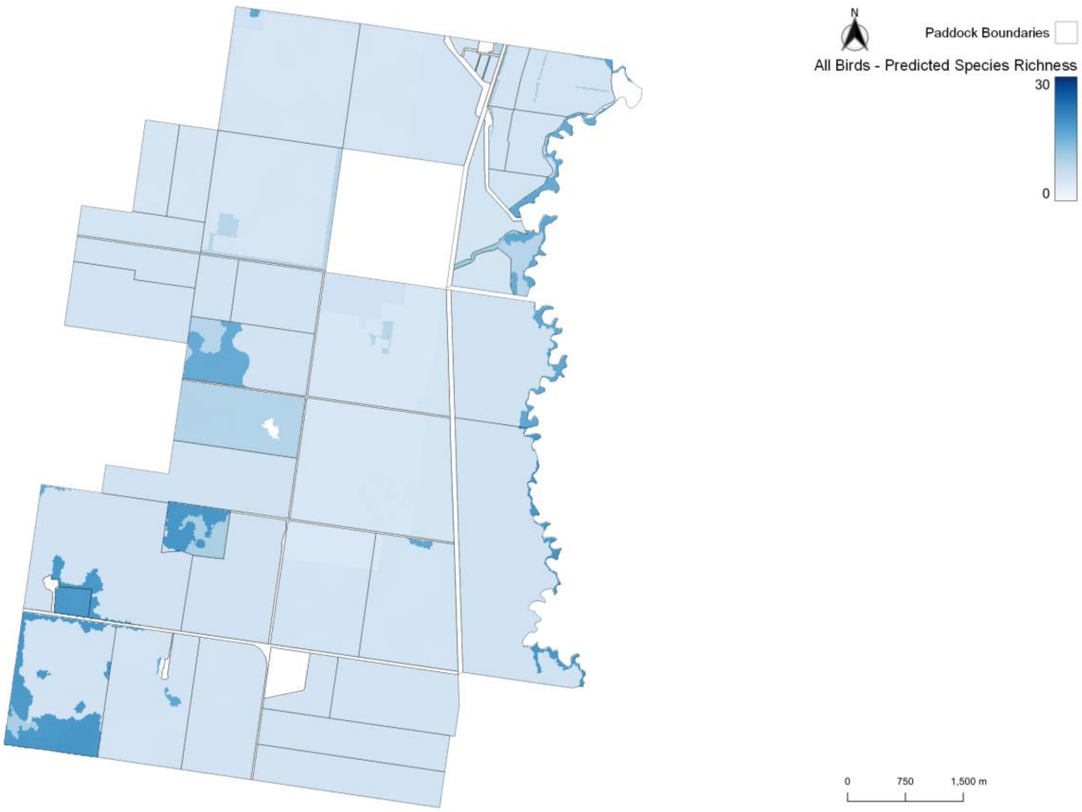

Figure 9. Example map of predicted species richness (for all birds per ha).

Based on the entire data set of 1155 sites for birds and 1090 sites for plants, we then assigned thresholds of species richness based on quantiles (25%, 50%, 75%, 90%) corresponding to 'poor' (<25%), 'moderate' (26-50%), 'good' (51-75%, 'very good' (76-90%), or 'outstanding' (>90%) quality habitat for each group of birds and plants (Table 6). The biodiversity asset accounts (Table 7) were then generated by summing the area within each of the habitat quality categories across the farm. These habitat quality categories and species richness thresholds can be used to generate accounts for other farms within the bioregions represented in our original dataset. For farms outside this region, new assessments of habitat quality (i.e., different species richness thresholds or use of other indicators) may be required.

Table 6. Species richness thresholds used to assign habitat quality categories. Values are species richness expected from 4 x 10 min/1 ha surveys for birds and a 500 m2 plot for plants.

Taxon	Group	Habitat quality categories				
		Poor	Moderate	Good	Very good	Outstanding
Birds	All birds	0-6	7-10	11-15	16-21	>21
Birds	Woodland birds	0	0-1	2-5	6-11	>11
Birds	Grassland birds	0	n/a	1	n/a	>1
Plants	All plants	0-18	19-27	28-38	39-49	>49
Plants	All native plants	0-4	5-11	12-21	22-32	>32
Plants	Native shrubs	0	n/a	1-2	3-4	>4
Plants	Native ground layer	0-4	5-11	12-21	22-32	>32

Table 7. Example biodiversity account.

Group	Metric	Habitat quality				
		Poor	Moderate	Good	Very good	Outstanding
All birds	Area (ha)	4589.4	212.2	14.5	251.1	0.0
	% of farm	90.6%	4.2%	0.3%	5.0%	0.0%
Woodland birds	Area (ha)	4584.8	190.8	136.6	155.0	0.0
	% of farm	90.5%	3.8%	2.7%	3.1%	0.0%
Grassland birds	Area (ha)	279.2	N/A	1630.7	N/A	3157.4
	% of farm	5.5%	N/A	32.2%	N/A	62.3%
All plants	Area (ha)	3432.3	1305.3	329.7	0.0	0.0
	% of farm	67.7%	25.8%	6.5%	0.0%	0.0%
All native plants	Area (ha)	3432.3	1310.6	239.7	84.7	0.0
	% of farm	67.7%	25.9%	4.7%	1.7%	0.0%
Native ground layer	Area (ha)	3432.3	1313.0	300.8	21.2	0.0
	% of farm	67.7%	25.9%	5.9%	0.4%	0.0%
Native shrubs	Area (ha)	3490.3	N/A	1423.4	153.6	0.0
	% of farm	68.9%	N/A	28.1%	3.0%	0.0%

4 Quantification of Ecosystem Services

This section outlines how the estimates of various ecosystem services were generated for each farm. This includes services provided by invertebrates (decomposition, pollination, pest predation), soil regulation (ground cover), forage production, and shade and shelter services.

4.1 Ecosystem services supplied by invertebrates

To account for arthropod-mediated ecosystem services, the invertebrate community was sampled for decomposers, pollinators and predators (see Appendix C for sampling methods, genetic analysis and paddock-scale modelling). This section outlines how the summary accounts for each of the arthropod-mediated ecosystem services (decomposition, pollination, and predation) were generated.

We provided farmers with information about the abundance of arthropod decomposers and number of species of arthropod predators and pollinators found on their farm, as well as the extent and quality of habitat for each group of organisms. The diversity measures provide an indication of the value of the habitat to these groups and the maps indicate where on the farm ecosystem services provided by arthropod decomposers, pollinators and predators are predicted to be higher or lower.

4.1.1 Explanatory variables

We used a model selection approach to determine the combination of explanatory variables to include in the final model for each group of interest. The variables that were included in the models are described in Table 8. The source and processing for the elevation and height above nearest drainage (HAND) variables were the same as those described for birds and plants. For the decomposer community model, ecosystem states were combined into five classes based on structural attributes of the ecosystem type (Table 9). This was done because the decomposer community samples were collected from Victoria only, and not all ecosystem classes were represented in the decomposer sampling sites. For the predator and pollinator community models, ecosystem states were combined to recognise the full set of ecosystem states (as described for birds and plants) (Table 10).

Table 8. Explanatory variables included in models to explain the diversity of beneficial arthropods.

Variable	Variable name in model	Scale	Unit	Description	Models that included the variable
Ecosystem state	EcoType	Patch	Category	A categorical variable based on the ecosystem states defined in the state-and-transition models. For spatial predictions, categories were assigned numeric values that correspond to the raster layers for each farm.	All models *
Proximity to trees	Treeprox	Site	m	A measure of the distance to the nearest tree (see Section 6.3)	All models
Proximity to ecosystem state edge	Ecoprox	Site	m	A measure of the distance to the edge of the ecosystem state	All models
Patch size	Patch	Patch	ha(log)	Area of contiguous habitat connected to the survey site	Predators, Pollinators
Height above nearest drainage	HAND	Site	m	Vertical height above the nearest named drainage system. Derived from a digital elevation model.	All models
Fractional ground cover	FGC	Site	%	Mean Ground Cover 10th percentile across the 5 years from 2016-20.	All models
Elevation	Elevation	Site	m	Height above sea level.	Predators, pollinators
Rainfall	Rainfall	Farm	mm	Mean rainfall for the farm, sourced from the Australian Government (Long term average rainfall map layer).	All models

* Ecosystem states recognised in this layer differed for decomposers; see Table and Table .

Table 9. Ecosystem state categories that were combined into five categories for the decomposer model.

Ecosystem state code	Description	States included from STMs
1	Crops with or without scattered trees.	C1, C2, C3
2	High diversity grasslands. May or may not have scattered trees. Mostly native with some exotic species.	RG, RGt, DG1, MG1, DG2, MG2, DG1t, MG1t, DG2t, MG2t
3	Derived grassland with scattered trees. Mostly exotic with few native species.	DG3t, MG3t, DG4t, MG4t, DG3, MG3, DG4, MG4
4	Derived entirely exotic grassland with scattered trees.	DG5t, MG5t, DG6t, MG6t, DG5, MG5, DG6, MG6
5	Woody vegetation types, including thickets and planted trees.	RW, RF, TW1, TF1, DF1, TW2, TF2, DF2, TW3, TF3, DF3, TW4, TF4, DF4, TW5, TF5, DF5, TW6, TF6, DF6, DS3, DS4, TS3, TS4, PNT1, PNT2, PNT3, PNS2, EWV1, EWV2, EWV3

Table 10. Ecosystem state categories that were included in the ecosystem state variable for arthropod pollinators and predators.

Ecosystem state code	Description	States included from STMs
1	Native woodland or forest with very high diversity relative to local benchmarks. No exotic species. 'Best on offer'.	RW, RF
2	Woodland or forest (canopy cover 15 – 70%) with high native diversity. Few exotic species.	TW1, TF1, DF1
3	Woodland or forest (canopy cover 15 – 70%) with mostly native understorey. Some exotic species.	TW2, TF2, DF2
4	Woodland or forest (canopy cover 5 – 70%) with mostly exotic understorey.	TW3, TF3, DF3
5	Woodland or forest (canopy cover 5 – 50%) with entirely exotic understorey.	TW4, TF4, DF4
6	Dense thicket of regenerating canopy trees. Often patchily distributed around mature trees.	TW5, TF5, DF5, TW6, TF6, DF6
7	Reference grassland with scattered trees. Very high diversity. 'Best on offer'.	RGt
8	Derived native grassland with scattered trees. High native diversity and few exotic species.	DG1t, MG1t
9	Derived mixed grassland with scattered trees. Mostly native with some exotic species.	DG2t, MG2t
10	Derived grassland with scattered trees. Mostly exotic with few native species.	DG3t, MG3t
11	Derived exotic grassland with scattered trees. Very few native species.	DG4t, MG4t
12	Derived entirely exotic grassland with scattered trees.	DG5t, MG5t, DG6t, MG6t
13	Reference grassland. Very high diversity. 'Best on offer'.	RG
14	Derived native grassland with high diversity and few exotic species.	DG1, MG1
15	Derived mixed grassland, mostly native with some exotic species.	DG2, MG2
16	Derived grassland, mostly exotic with few native species.	DG3, MG3
17	Derived exotic grassland with very few native species.	DG4, MG4
18	Derived entirely exotic grassland.	DG5, MG5, DG6, MG6
19	Native shrubland (shrub cover >10%) with mostly native ground layer.	DS1, DS2, TS1, TS2
20	Native shrubland (shrub cover >10%) with mostly exotic ground layer.	DS3, DS4, TS3, TS4
21	Planted native trees 0 – 10 years.	PNT1
22	Planted native trees 11 – 40 years.	PNT2
23	Planted native trees >40 years.	PNT3
24	Planted native shrubs >3 years.	PNS2
25	Exotic trees. Canopy cover >5%.	EWV1
26	Exotic shrubland. Canopy cover <5%. Shrub cover >10%.	EWV2
27	Perennial horticulture (olive groves).	EWV3
28	Crops with scattered trees.	C1
29	Crops without scattered trees.	C2, C3

4.1.2 Modelling approach

Generalised Additive Models (GAMs) were used to generate spatially explicit predictions for ecosystem services on farms. The maps in the accounts show the predicted decomposer abundance (i.e., number of individuals) per square metre (to a depth of 5 cm) and species richness (number of species) per transect (50 sweeps) for pollinators and predators across the farm. These are derived from statistical models that used remotely sensed spatial variables to predict the abundance or richness of arthropods that provide ecosystem services on a farm. The models for decomposers were based on data collected from 411 samples from 83 sites across 15 farms, while the models for pollinators and predators were based on data collected from 636 samples from 130 sites across 36 farms in south-east Australia (see Appendix E).

4.1.2.1 Generating ecosystem service accounts for farms

To generate accounts of arthropod-mediated ecosystem services on farms, raster layers of each of the explanatory variables described in Table were used. Rainfall was used in all models to account for the influence of bioregion on arthropod diversity across regions. The model equations used to generate the arthropod-mediated ecosystem service accounts, in R language, can be found in Table 11.

Table 11. Generalised Additive Model (GAM) equations used to generate arthropod-mediated ecosystem service accounts for the Natural Capital Accounting project farms.

Response	Model structure	Deviance explained (%)
Decomposer abundance	Decomposer_abundance ~ s(Ecoprox, k=4) + EcoType + s(Treeprox, by=EcoType, k=3) + s(FGC, k=4) + s(HAND, k=3) + s(Rainfall, k=3), family=poisson, data = [dataframe]	12.1
Predator richness	Predator_richness ~ Eco.Type + s(Ecoprox, k=3) + s(Treeprox, k=3) + s(HAND, k=3) + s(Elevation, k=3) + s(Patch, k=3) + s(FGC, k=3) + s(Rainfall, k=3), family = poisson, data = [dataframe]	15.8
Pollinator richness	Pollinator_richness ~ s(Ecoprox, k=3) + Eco.Type + s(Treeprox, k=3) + s(HAND, k=3) + s(Elevation, k=3) + s(Patch, k=3) + s(FGC, k=3) + s(Rainfall, k=3), family = poisson, data = [dataframe]	35.7

4.1.2.2 Spatial predictions

As for birds and plants, we generated spatial predictions of abundance or species richness for each group of arthropods. These spatially explicit models indicate areas on the farm that are predicted to support more, or fewer, individuals or species of each group (e.g., Figure 10 and Figure 11). Raster layers of each explanatory variable were generated for each farm in QGIS at a resolution of 10 x 10 m. GAMs were built using the mgcv package and spatial predictions were generated using the Raster package in R. The arthropod models are stored as RDA files that can be loaded in R and used to predict to new farms within south-east Australia. The RDA files are available upon request from the La Trobe project team.

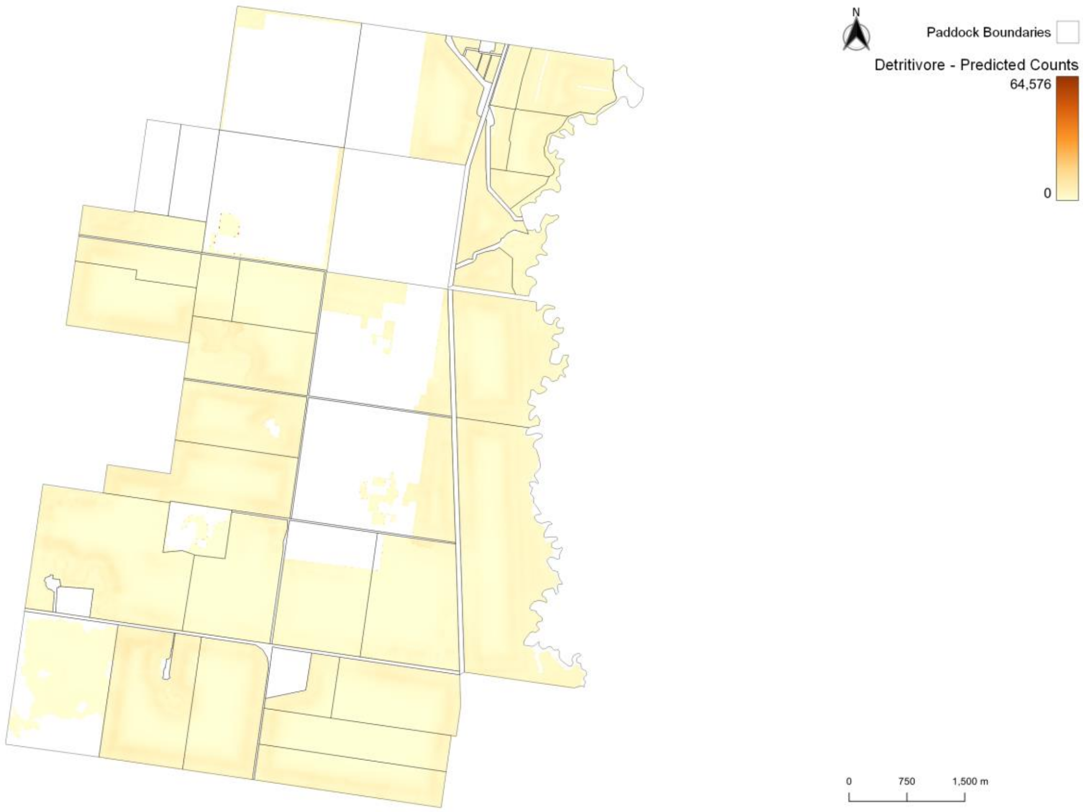

Figure 10. Mapped example of the predicted decomposer abundance on a farm.

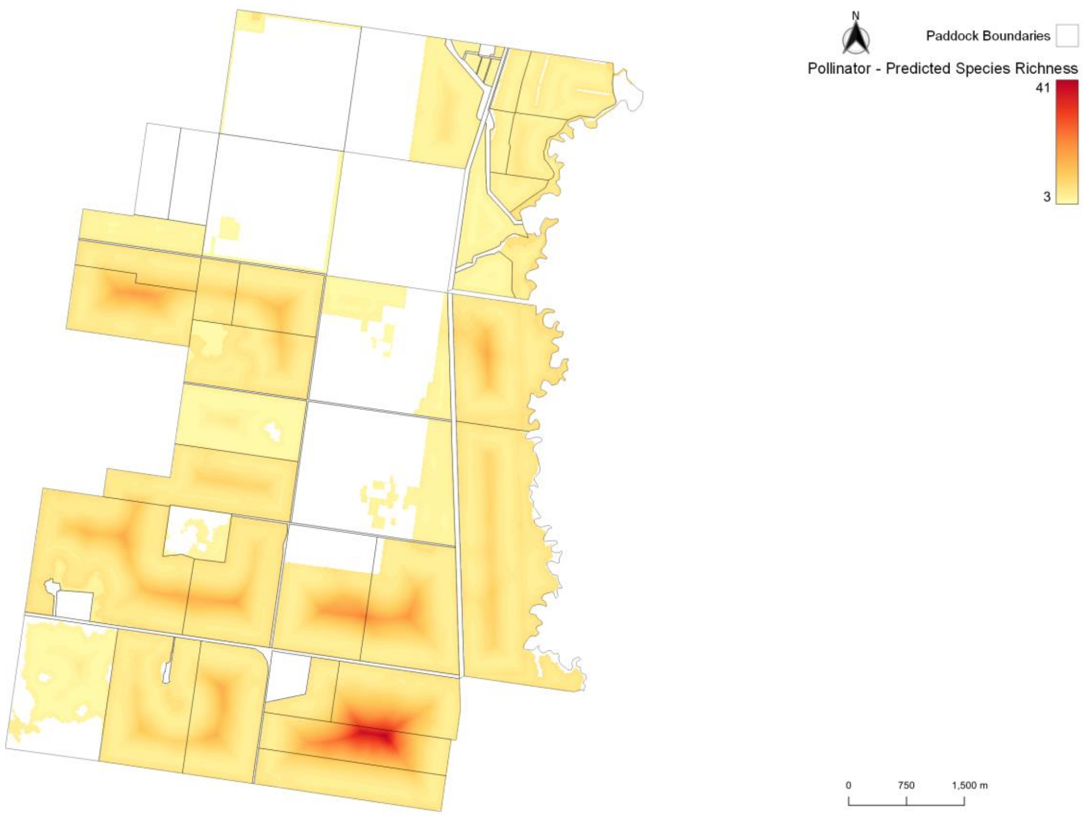

Figure 11. Mapped example of the predicted pollinator richness on a farm.

4.1.3 Generating accounts of ecosystem services

For the decomposer community, we assigned thresholds of abundance based on farm-scale quantiles (25%, 50%, 75%, 90%) and reported the predicted abundance of decomposers at each quantile (Table 12). By reporting the predicted detritivore abundance for each quantile, change can be measured through time against this baseline. The highest quantile threshold provides a measure of the number of detritivores predicted at the 90th percentile (i.e. the minimum predicted number of decomposers in the top 5 cm litter/soil, per square metre in the best 10% of the farm). If habitat suitability for detritivores were to improve over time, the predicted abundance at these quantile thresholds would increase in future assessments (or conversely, if habitat suitability for detritivores were to decline, abundance values would decrease).

Table 12. Example of quantile thresholds used for detritivore abundance on farms.

Quantile	Predicted abundance
90%	4522
75%	3516
50%	2010
25%	520

For pollinator and predator groups, thresholds were applied to habitat quality quantiles. Using the entire data set of 636 sites, we assigned thresholds of species richness based on quantiles for which we considered 'poor' (<25%), 'moderate' (26-50%), 'good' (51-75%), 'very good' (76-90%), or 'outstanding' (>90%) quality habitat for both arthropod predators and pollinators. The species richness thresholds for each category equate to the following:

- Pollinators: 0-4 species/ 50m transect = poor, 5-7 = moderate, 8-12 = good, 12-17 = very good, >17 = outstanding.
- Predators: 0-1 species/ 50m transect = poor, 2 = moderate, 3 = good, 4 = very good, >4 = outstanding.

The ecosystem service accounts were then generated by summing the area within each of the habitat quality categories (poor to outstanding) across the farm (Table 13). These habitat quality categories and species richness thresholds can be used to generate accounts for other farms within the bioregions represented in our original dataset. For farms outside this region, new assessments of habitat quality (i.e., different species richness thresholds or use of other indicators) may be required.

Table 13. Example of habitat quality reported for different invertebrate groups on a farm.

Plant group	Metric	Habitat quality				
		Poor	Moderate	Good	Very good	Outstanding
Pollinators	**Area (ha)**	0.1	1498.3	1856.1	228.8	99.4
	% of farm	<0.01%	40.7%	50.4%	6.2%	2.7%
Predators	**Area (ha)**	127.1	2921.4	540.9	80.0	13.3
	% of farm	3.5%	79.3%	14.7%	2.2%	0.4%

4.2 Soil Regulation Services

The physical, chemical, and biological properties of soil determine its capacity to store and supply soil-water, substrate and nutrients for multiple natural capital assets: native ecosystems, planted vegetation and particularly, intensive land-use systems, including crops and pastures. However, there is no widely-accepted definition of soil quality or soil health (i.e., a desirable value or range for specified soil attributes) nor how soil quality can be quantified in a way that is predictive of the type and amount of ecosystem services soil will generate (Powlson 2020, Philippot et al. 2023). Indeed, soil quality / soil health will be strongly influenced by the intended land use (e.g., to support native vegetation, pastures, crops of different sorts) such that low values of an attribute (e.g., soil P) may be desirable for one use (e.g., native grasslands) but undesirable for another (e.g., cropping) and vice-versa (Giller et al. 2021). In the absence of an agreed definition of soil health or cost-effective methods to measure key attributes of soil condition at spatial and temporal scales that reflect farm management practices, we have used ground cover as a surrogate for soil regulation services.

Ground cover is the extent to which the land surface is covered by live and/or dead plant material. This includes all live plants in contact with the ground (grasses, forbs, herbs, shrubs), cryptograms (e.g., mosses, lichens) and dead plant matter (litter). Ground cover contributes to several regulating services (e.g., soil fertility, soil erosion control, regulation of water flow) and provisioning services (e.g., freshwater, forage).

Ground cover is also a key factor in the capacity of a farm to produce several ecosystem services. Ground cover slows surface water flows following rain, thus increasing water infiltration into the soil and filtering sediments and particles from water. This improves the quality of water flowing into dams, drainages and waterways, and increases soil moisture. Maintaining ground cover also reduces evaporation from soil, protects the soil surface from water and wind erosion and contributes organic matter into the soil, reducing erosion and improving soil fertility.

4.2.1 Calculating ground cover statistics

Ground cover is derived from remote sensed Landsat satellite imagery, which collects data from a farm approximately every 6 days at a spatial resolution of 30 m x 30 m. We sourced the data from the Fractional Cover 25m Percentiles 2.2.1 product from Digital Earth Australia (Lymburner 2021). These data provide annual 10th, 50th and 90th percentiles (i.e., the percentiles across all images collected in a year) of fractional cover for photosynthetically-active plant material (living plants), photosynthetically-inactive plant material (dead material, litter), and bare earth (bare ground) for each pixel, each expressed as a proportion from 0-1, and summing to 1. We used (1 - bare ground) as a proxy for total ground cover (live and dead material).

To calculate ground cover, we first applied a tree mask over each farm to remove pixels attributed to tree canopy. We then collated the minimum (10th percentile) and mean (50th percentile) ground cover for each and every non-tree pixel within the farm boundary for each of the last 5 years (2018 to 2022). Thus, each pixel has a value for minimum and mean ground cover for each year. For example, a pixel may have a minimum (10th percentile) value of 27% ground cover, and an average (50th percentile) of 67% ground cover, in a given year. We then calculated the proportion of the farm that maintained a minimum ground cover value at or above 70% cover at all times during each year. We chose a threshold of 70% because below this value, the risk of soil erosion accelerates.

We then calculated the average value of all non-tree pixels of the minimum and mean ground cover for each of the last 5 years, giving us 5 annual minimum (10th percentile) and mean (50th percentile) raster datasets. We then plotted the annual average minimum, average mean, and proportion of the farm always above 70% ground cover for each for the last five years (Figure 12). We included annual and monthly rainfall in this plot because rainfall is a key factor in the ability to generate and retain groundcover (See 5.1.7 for calculation of rainfall data).

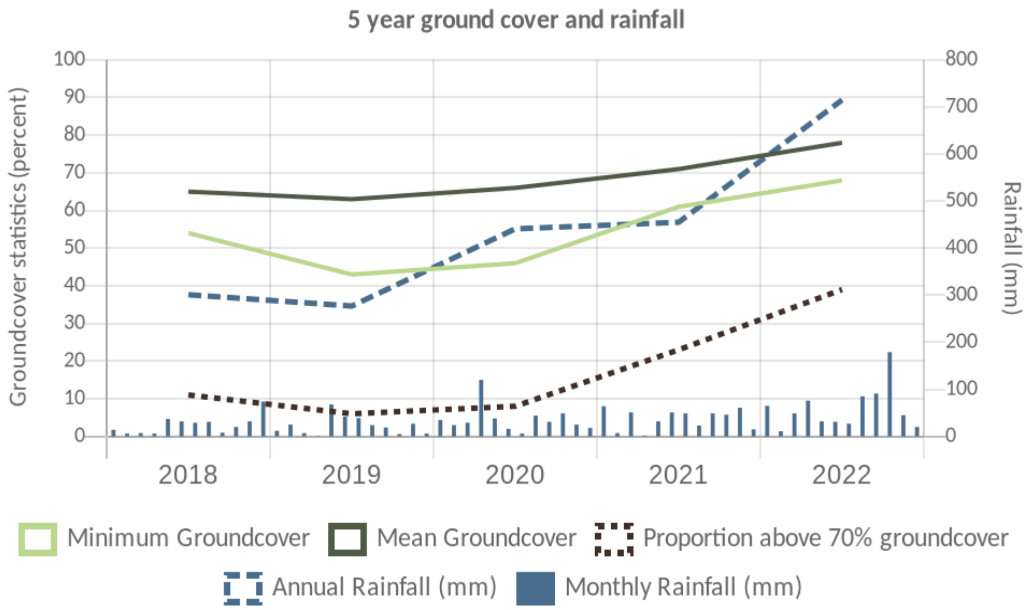

Figure 12. Example ground cover vs rainfall plot (2018-2022)

A 5-year average was calculated for each of the annual metrics (minimum, mean and proportion below 70%). We presented this data, along with the values for the most recent year (2022 in this case) in Table 14. We used a 5-year temporal mean to smooth seasonal variation and to reduce the influence of weather conditions of the previous year (i.e. wetter or dryer conditions) on a farm's ground cover metrics.

We also generated maps of the minimum ground cover in 2022 and the mean minimum ground cover for the 2018-2022 time period.

Table 14. Example ground cover statistics for 2022 and 5-year mean (2018-2022)

Description	Metric for 2022	5-year mean to 2022
Mean minimum groundcover	68 %	55 %
Percentage of farm with minimum groundcover above 70%	39 %	18 %
Mean modelled rainfall	716 mm	438 mm

4.3 Forage Production Services

4.3.1 Forage condition for grazing

Forage Condition is the capacity of the land to produce resilient and high-quality forage for livestock. The objective for forage condition classification is to provide insights that support farmer management of natural capital. The capacity of the farm's natural capital to provide forage for livestock grazing through a range of climatic conditions was quantified by placing each paddock into a forage classification (A, B, C and D) with the total area in each condition reported for the property. Classifications were designed to enable the tracking of condition change over time at a property scale from a production perspective and to be useful to a farmer in making decisions about future management.

The analysis characterises the capacity of each Ecosystem Unit to dependably produce high quality forage for livestock. The classification of paddocks drew heavily on industry grazing condition guidance communicated over the past two decades (Mason et. al. 2003; Meat Livestock Australia 2006; Gardiner and Reid 2010). These frameworks recognize that palatable, persistent and perennial pastures that are also productive (i.e., the '3P' grasses and shrubs) are the backbone of sustainable and productive pastures. Species origin (i.e., native or introduced) is less important than their palatability to livestock, perenniality, productivity and their ability to tolerate and persist under grazing, including conditions of drought. Season of growth is also important.

The forage condition classification process was adapted (in consultation with Robert Hassett) from the Land Condition Assessment Tool (LCAT; Hassett 2020). The LCAT method has refined the ABCD grazing land condition framework (used by many organisations including Meat and Livestock Australia (MLA)) by quantifying the contribution of different pasture species as a measure of the capacity of the land to produce valuable forage for livestock. This approach was chosen following previous project experience working across a range of sown, naturalised and native pastures, discussions with Brett Abbott – author of CSIRO's PatchKey (Abbot and Corfield 2012) – and reviewing relevant MLA documentation such as Pasture Paramedic (MLA 2020). LCAT took an approach that allowed us to recognise the valuable characteristics of pastures with a high proportion of native species in them (which may be characteristics that suit a farmer's goals and aspirations well). This contrasts to Pasture Paramedic which predominantly focuses on a small group of high-yielding sown species. It is not implied that the approach of Pasture Paramedic is incorrect, rather that our approach aligned with the hypothesis that diverse, perennial pastures provide a resilient forage base during varying climatic conditions. We also consulted with a group of expert farmers (with a variety of perspectives) regarding species forage values. Accordingly, the pasture condition score is determined by the overall degree of perenniality, palatability, productivity and persistence of pastures, with some acknowledgment of the value of diversity (to impart resilience, persistence and productivity through a range of climatic conditions).

These categories also apply to the understorey of grassy woodland and forest areas that are grazed in temperate regions. The condition of forage resources in woodlands and forests is affected by long-term management decisions and by short-term patterns of grazing and quality of seasons. Accordingly, the measures are intended to apply the concept of dynamic reference condition as far as practical. This is achieved by providing a very similar 'score' independent of whether the site has been recently grazed, or whether it is a favourable or less favourable season. However, assessments are challenging with drought and flood conditions.

4.3.2 Data collection for forage classification

To gather pasture condition information, between 3 and 5 assessments are undertaken at individual points, with the number being determined by how variable the ground layer is across the sample area (as per

Section 2.4.2.3). The pasture condition score is calculated post-hoc from the data gathered. The method used for these individual point assessments aligns with (and has been adapted from) the LCAT.

At each of 3 to 5 assessment points, the sward is assessed within a 2 m radius circle and a photograph of the sward is taken. Data recorded includes:

- sward height (where sward is homogenous)
- the five most dominant plant species are recorded with species 1 the most dominant species and plant species 5 is the fifth most dominant species.
- For each of these species (up to 5) the following information is recorded:
- Plant species density (Table 15)
- Where sward is not homogenous, estimate plant species average height (not including seed heads and stems)
- Density of all perennial herbaceous plants combined (i.e. overall sward density but excluding annual component).
- % ground cover (percentage of the soil protected by organic cover). This includes plants, plant litter (both attached and unattached), woody litter (<5cm diameter) and cryptograms.
- Plant litter cover and depth. Litter refers to both attached and detached plant material within 5cm of the soil surface.

Table 15. Category of observed species density

Plant type density category	Description
Closed Dense (CD)	Touching-overlapping canopies. Slightly separated bases.
Moderately Dense (MD)	Touching-slightly separated canopies. Clearly separated bases.
Sparce or Open (SO)	Clearly separated canopies. Well-separated bases.
Very Sparce (VS)	Well separated canopies. Very well separated bases.
Isolated (IS)	Isolated canopies. Isolated bases.
Not observed (NN)	NA

4.3.3 Calculation of forage condition score

Each ground-layer or shrub plant observed in the data collected is assigned a category according to its qualities as a forage plant for livestock (Table 16). We follow (with a slight modification as explained below) Gardiner and Reid's (2010) description of the components of a pasture sward that contribute to a sustainable and productive temperate pasture. Gardiner and Reid (2010; p453) describe such a pasture as one that: "maintain(s) pasture composition in terms of palatable, persistent, perennial grasses, responsive legumes and palatable 'gap fillers'": No distinction was made between the preferences of sheep and cattle (or other livestock classes).

We have created a database where species are given a unique value depending on their physiological characteristics that contribute to resilient forage production, such as perenniality, productivity, palatability and persistence. These values are scaled accordingly, for example a perennial 3P species will score higher than a perennial 2P (that is lacking a key characteristic of either productivity or palatability). Likewise, a perennial grass or forb will score higher than an annual grass or forb due to the increased landscape resilience and function it imparts. Increased value is also assigned to annual pasture and perennial forb species when they are filling gaps in the sward (Gardiner and Reid 2010). Species contributing no grazing value or threatening the condition of the land (i.e., recognized weedy species) are given 0 value.

In addition to >60% cover of 3P grasses, experts emphasise the importance of two additional pasture components. First, responsive legumes provide perennial grasses with nitrogen in N-deficient soils (it is often economic to ensure adequate soil nutrition and an active legume component such as clovers and medics). Second, the remaining space in pasture not occupied by 3P grasses and legumes should consist of 'gap-fillers' (i.e., palatable, productive broad-leaved herbs such as plantains and chicory, and palatable annual grasses such as bromes). Gap-fillers contribute to pasture phenological and nutritional diversity, competitively exclude weeds. Annuals also have a higher Radiation-use efficiency (RUE) than perennials (Gardiner, 2010). Future phases will incorporate information about whether the species are summer or winter growing. This will be used to assess the degree to which pastures will be productive all year round.

Table 16. Categories of plant quality for livestock forage.

Category	Description
3P	Palatable, productive and perennial grasses
2P	Grasses with two of the possible 3P characteristics
1P	Grasses with one of the possible 3P characteristics
GFP	Gap Filler Perennials
AV	Valuable annuals – an annual species that is considered valuable as a forage plant
V	Generic annuals
NO	No value for forage.

The quality of the species and the density of them in the sward were used as inputs to calculate the forage condition score for each observed sward (Figure 13). Scores are calculated by combining these species categories with weighted values according to their dominance and density in the sward. The scores for all the species in the sward are then summed to provide a single score for the sward.

Farm	Audit ID	Site ID	Sward Class	Score
Code: XXX	audit_bcc476d8ac194ec99484c2266765ec2b	Alt. B9 WL - P2	**B**	**107**
Comments:				
	Sp. Name	**Density**	**Species Classification**	**Model 3 SCORE**
Sp1	***Festuca arundinacea - Fescue**	**Mid-dense**	3P	53
Sp2	**Chloris truncata - Windmill grass**	**Very Sparse**	2P	16
Sp3	**Eragrostis leptostachya - Paddock lovegrass**	**Isolated**	3P	20
Sp4	***Trifolium repens - White clover**	**Very Sparse**	AV	18
Sp5	***Cirsium vulgare - Black thistle / Spear Thistle**	**Isolated**	NO	0

Figure 13. Example of forage condition calculations for an observed sward. The quality of the species is combined with its density to provide a score for the sward.

The average of the sward scores of the three to five points assessed was used as the score for the Ecosystem Unit. The averaged score is then used to assign a forage classification (ABCD) based on a set of thresholds (Table 17).

The grazing categorisation (Table 17) recognises the value of different types of pasture swards and encompasses exotic, native or mixed pastures and their characteristics of perenniality, palatability, persistence and productivity with some acknowledgement of the value of diversity (to impart persistence and productivity through a range of climatic conditions).

Some high scoring pastures may be more reliant on high inputs and good seasons while others may respond well to low input planned grazing. Different pastures will persist under different types of management depending on the farmer's goals and what species are desired, valued and managed for on each farm. Importantly, sward composition might be changed by altering management (if that is the goal of the farmer).

Table 17. Classifications used for forage condition.

Class	Thresholds	Description
A	> 135	A diverse mix of 3P species (perennial, palatable productive; >3 species). Gap filler species (valuable annuals and perennial forbs) can also be present.
B	> 80 to 135	Moderate perennial cover, but only one or two 3P species with 1P or 2P species making up the remainder of perennials. Some gap filler species are also likely to be present
C	> 40 to 80	Very sparse perennial cover. Likely to be mainly 1P or 2P species with occasional 3P species but at very low abundance. Gap filler and valuable annual species (including mixed annual sown pastures) may be present and/or weeds that contribute no value to forage production.
D	0 to 40	Almost no perennial species present. Pastures include annual sown monocultures or swards with low forage value (i.e., 1P species, less valuable annual species) and/or weeds with no forage value.

Lookup tables for the species categorisation, density weightings and thresholds for forage classification are available upon request from the project team.

4.4 Shade

Trees and shrubs provide amelioration of extreme temperatures which is associated with improved crop and livestock productivity. The amount of shade provided by trees is determined by the height and configuration of trees on a farm but is also influenced by time of day and time of year. We could not calculate the amount of shade generated as a continuous variable, integrated across all times of day and days of the year, so we devised the Shade Index (ShdI). The Shade Index is a measure of the extent (area) of shade provided by trees to production areas on a farm at a single point in time. We chose 3 pm on the summer solstice as the time at which to calculate ShdI because the middle of the afternoon in the middle of summer is hypothetically at least, when shade would provide the maximum ecosystem service benefit. The value presented is a surrogate for shade provision at other times throughout the day and year (i.e., a farm with a high ShdI is likely to have more shade at other times than a farm with lower ShdI).

4.4.1 Mapping Shade

The Shade Index is calculated by overlaying the tree canopy mask and a global canopy height model (Lang et al. 2023). To standardise across farms, the angle of the sun is determined by the farm location (a centroid latitude and longitude point) at 15:00 on the summer solstice using the *oce* package in R (Kelley and Kelley 2018). The Shade Index is then calculated using the sun angle divided by the height of the tree (ShdI = tan(sun angle) /canopy height). The values are calculated per pixel of tree cover and spatially projected in the approximate direction of afternoon shade (i.e., from west to east) (Figure 14). A 200 m buffer beyond the farm boundary is used to include the shade contributed by trees outside the farm boundary to the production areas. R codes for calculating and projecting shade are available upon request from the project team.

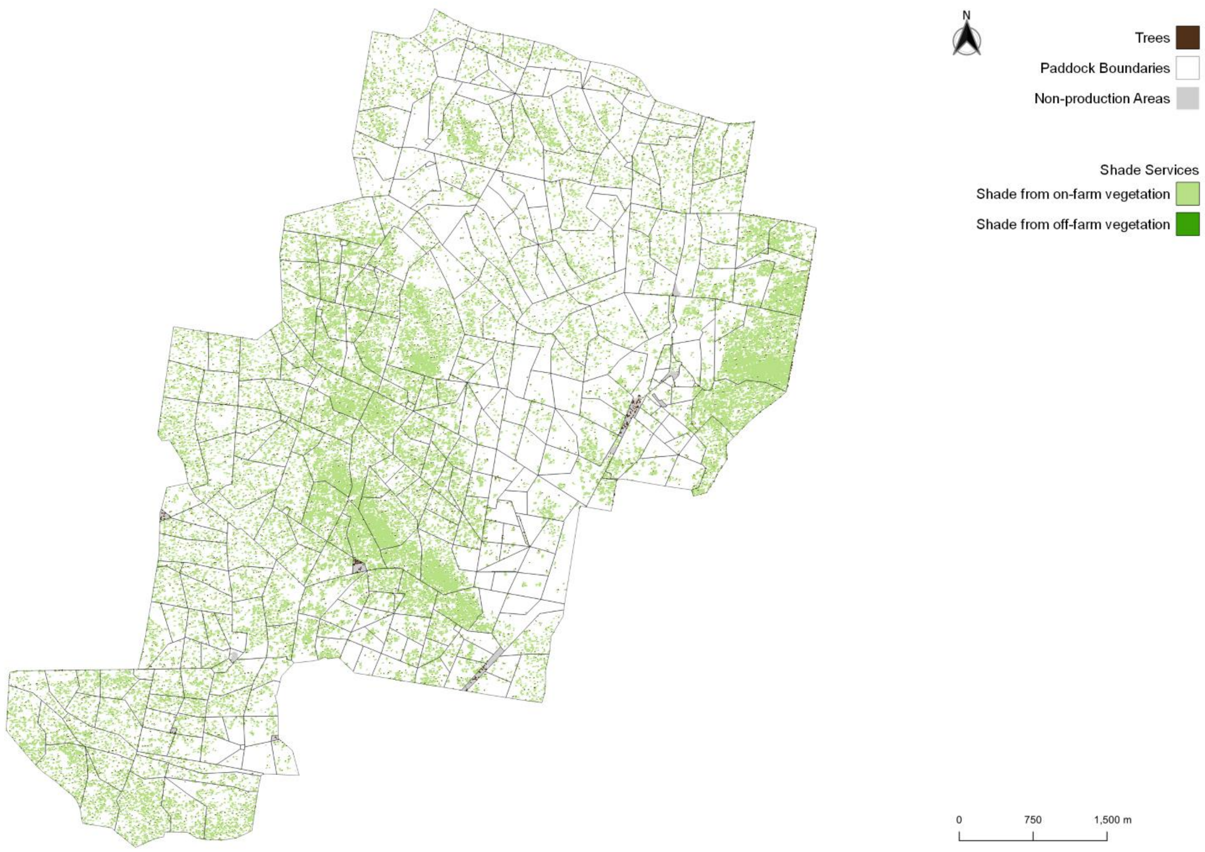

Figure 14. Example of shade ecosystem service provision

4.4.2 Calculating the Shade Index Account

The ShdI is calculated for production areas only (i.e., non-production areas excluded although trees in non-production areas can provide shade) and presented as the proportion of production area shaded (%).

$ShdI_{PRODUCTION}$ = Shaded production area/Total production area

As areas of the farm may benefit from shade services differently, $ShdI_{PRODUCTION}$ is separated into proportion of grazing areas shaded and proportion of cropping area shaded.

$ShdI_{GRAZING}$ = Shaded grazing area/Total grazing area

$ShdI_{CROPPING}$ = Shaded cropping area/Total cropping area

$ShdI_X$ were further categorised by the location of tree that is provisioning shade. Shade produced by trees within the farm boundary is distinguished from shade provided by trees outside the farm boundary.

ShdI is presented as the percentage of production areas receiving shade (Table 18). Farm with values approaching 0 have very little shaded production areas and farms with values approaching 100 have nearly all production areas are shaded.

Table 18. Example of Shade ecosystem service account

Shade Type	Production areas shaded (ha)	Proportion of production areas shaded	Grazing areas shaded (ha)	Proportion of grazing areas shaded	Cropping areas shaded (ha)	Proportion of cropping areas shaded
On farm	54.3	1.1%	41.5	2.6%	54.3	1.6%
Off farm	0.0	0.0%	0.0	0.0%	0.0	0.0%

4.5 Shelter (wind protection)

Reduction of wind chill, frost and cold is important on livestock properties, with survival and lambing success positively correlated with shelter in cold and wet conditions. In cropping enterprises, shelter reduces wind speed, soil erosion, loss of soil moisture and is most beneficial in hot and dry climates. These ecosystem services are also relevant for pasture productivity and yields on livestock enterprises. Shelterbelts are known to protect up to 20 times the height of the canopy while scattered trees in paddocks and patches of contiguous canopy have a lower protection multiplier. The parameters used in this model are informed by results from the CSIRO Perennial Prosperity project, which is seeking to quantify the benefits of farm forestry for agricultural production.

4.5.1 Mapping Shelter

Shelter is calculated by overlaying the tree canopy mask and a global canopy height model (Lang et al. 2023) for all trees within a 500 m buffer beyond the farm boundary. For trees within the farm boundary, the location of the tree was intersected with Ecosystem State which was used to assign relevant protection multipliers. Three types of shelter were identified across the farm, each with varying degrees of protection capacity. These were linear shelter belts (PNT, EWV1), scattered trees (RGt, DG_xt, MG_xt, DS, C1) and contiguous blocks of trees (RW/RF, TW_x, TF_x; see Appendix A for details of the STMs). The protection multipliers assigned were 16 (linear shelter belts), 5 (scattered trees) and 7 (contiguous blocks) times the tree height.

For trees located outside the farm boundary, it was not possible to categorise woody vegetation by Ecosystem State. However, much of this is likely to be road-side woody vegetation with shelter properties similar to shelterbelts. As such, they were assigned the maximum protection factor (i.e., 16 times tree height).

Shelter was calculated for each pixel of tree cover and spatially projected to map the shelter afforded to production areas for harsh cold winter (south-west) and hot summer (north-west) winds (Figure 15). R codes for calculating and projecting shelter are available upon request from the project team.

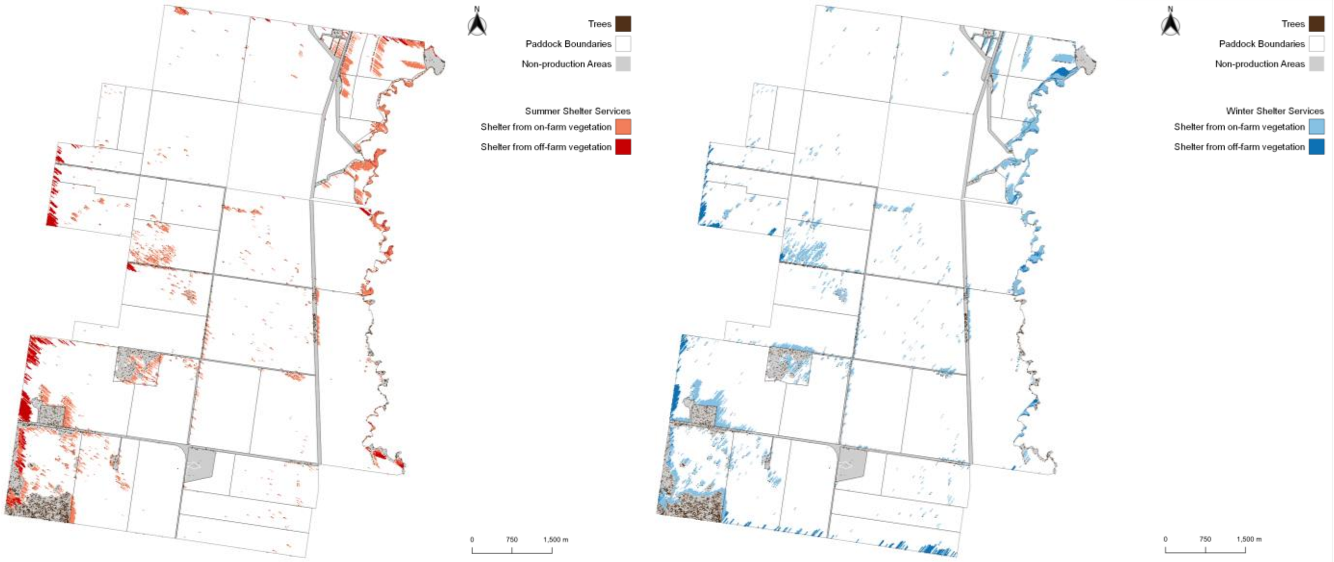

Figure 15. Example of provision of shelter ecosystem services: protection from summer hot winds (left) and cold winter winds (right).

4.5.2 Calculating the Shelter Index Account

The Shelter Index is calculated for production areas only (i.e., non-production areas excluded although trees in non-production areas can provide shelter) and presented as the proportion of production area afforded protection from either hot summer winds or cold winter winds.

$Shel_{PRODUCTION}$ = Sheltered production area/Total production area

As areas of the farm may benefit from shade services differently, $Shel_{PRODUCTION}$ is separated into proportions based on production type (i.e., proportion of grazing or cropping area afforded shelter).

$Shelter_{GRAZING}$ = Sheltered grazing area/Total grazing area

$Shelter_{CROPPING}$ = Sheltered cropping area/Total cropping area

Shel are further categorised by the location of tree that is provisioning shade (i.e., if the tree was present within the farm boundary or outside the farm boundary).

Shel is presented as the percentage of production areas on a farm receiving shelter services (Table 19). Farms with values approaching 0 have very little wind protection and farms with values approaching 100 have nearly complete protection of the production areas from wind.

Table 19. Example of Shelter ecosystem service account.

Shelter Type	Production areas sheltered (ha)	Proportion of production areas sheltered	Grazing areas sheltered (ha)	Proportion of grazing areas sheltered	Cropping areas sheltered (ha)	Proportion of cropping areas sheltered
Summer - on farm	168.7	3.4%	97.9	6.2%	71.5	2.1%
Summer - off farm	51.5	1.0%	13.6	0.9%	37.9	1.1%
Winter - on farm	223.6	4.5%	123.4	7.8%	101.1	3.0%
Winter - off farm	45.1	0.9%	8.6	0.5%	36.5	1.1%

5 Quantification of Environmental Performance Metrics

This section outlines how the environmental performance metrics were generated for each farm. The accounts provide estimates of the total greenhouse gas (GHG) emissions generated from farm operations, as well as outlining the estimates of water pollution, waste, water use, Nitrogen/Phosphorus/Lime use and GHG emissions per kg of product (wool, sheep liveweight, cattle liveweight, and crop).

These metrics were calculated for each farm based on 5 years of farm production data supplied by the farm business. The environmental performance metrics are calculated as an average estimate over this multi-year period to account for interannual variation in seasonal and market conditions and to remove the distortions that can occur in the metrics due to the timing of business activities (e.g. the timing of the purchase or sale of livestock, or the timing of purchase and application of fertiliser).

5.1 Calculation of GHG emissions

5.1.1 Scope 1 emissions

Scope 1 emissions were calculated for on-farm operations including fuel and fertilizer use, livestock operations, and cropping operations.

The emissions associated with fuel use (diesel, petrol, and gas) were estimated using the factors outlined in the National Greenhouse Accounts Factors – August 2021 (Department of Industry, Science and Resources (DISER) 2021). Where the farmer was unable to provide physical quantities of purchased diesel and petrol, the farmer provided annual $ spent for each commodity. These figures were converted to litres using the annual average pump price for the state as per the Fleet Auto News website[1].

The livestock emissions were calculated according to the methods described in the National Inventory Report 2020 (DISER 2022). The primary inputs for these calculations include:

- Flock numbers by season and class of animal (breeding ewes > 2 years, maiden ewes 1-2 years, other ewes (dry), weaned lambs < 1 year, hoggets 1-2 years, wethers > 2 years, rams)
- Herd numbers by season and class of animals (cows < 1 year, cows 1–2 years, cows > 2 years, steers < 1 year, steers > 1 year, bulls < 1 year, bulls > 1 year)
- Liveweight and liveweight gain estimates by season and class of animal:
- defined per flock or herd based on average weight of ewe/cow at joining, the season of lambing/calving, and the average birth weight, sale weight of lambs/steers, and the average sale age of lambs/steers. These metrics are used to localise the liveweight models provided per state in the NIR appendices.
- The state-based models provided in the NIR appendices were used where farm-specific models were not able to be calculated.
- Crude protein, dry matter digestibility, feed availability, and cattle and sheep reference weight models defined for each state in the NIR appendices.

The emissions associated with fertilizer use were calculated according to the methods described in section 5.6 of the National Inventory Report 2020 (DISER 2022). This includes emissions associated with the application of inorganic and organic fertilisers, crop and pasture residues, atmospheric deposition, and leaching and runoff. Note that leaching and runoff from fertiliser and manure application was considered to

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[1] https://fleetautonews.com.au/historical-pump-prices-in-australia/

be zero when the farm was located in a zone where Et/P was between 0.8 and 1 as per the map provided in section 5.6.10 of the NIR.

5.1.2 Scope 2 emissions

Scope 2 emissions were calculated for on-farm use of electricity associated with the livestock and cropping enterprises using the emissions factors provided in the National Greenhouse Accounts Factors – August 2021 (DISER 2021). Scope 2 emission calculations excluded electricity used for domestic purposes.

5.1.3 Scope 3 emissions

Scope 3 (pre-farm) emissions were calculated for the primary inputs to the livestock and cropping enterprises, including purchased livestock, fertilizer and other cropping/pasture inputs, fuel and electricity, and transport of those goods. The emission factors used to calculate scope 3 emissions are shown in Table 20.

Table 20. Pre-farm emission factors for purchased products.

Pre-farm input	Emissions factor	Emissions factor source
Fuel (diesel, petrol)	As per factors tables	National Greenhouse Accounts Factors – August 2021
Electricity	As per factors tables	National Greenhouse Accounts Factors – August 2021
Live sheep purchases	9.3 kg CO_2e/kg LWT	(Wiedemann et al., 2016)
Live cattle purchases: **NSW/ACT/VIC/SA/TAS** **QLD/WA/NT**	 11.7 kg CO_2e/kg LWT 12.4 kg CO_2e/kg LWT	(Wiedemann et al., 2015b)
Glyphosate/Diquat/ Paraquat based herbicides	33 kg CO_2e/litre	(O'Halloran et al., 2008)
Other herbicides and other additives (surfactants etc)	18.75 kg CO_2e/litre	
N-P-K-S fertilisers	Calculated based on percentage of each component	
Lime	0.432 kg CO_2e/kg	
Gypsum	0.45 kg CO_2e/kg	
Purchased feed (grain)	0.30 kg CO_2e/kg	(Christie et al., 2011)
Purchased feed (hay/silage)	0.25 kg CO_2e/kg	
Purchased feed (lucerne)	0.20 kg CO_2e/kg	

Whilst the emissions sources included in the scope 3 emissions calculations are a material proportion of the total scope 3 emissions for a farm, they aren't a complete set of emissions sources for scope 3 according to the GHG Protocol Scope 3 standard[2]. The inclusions and exclusions are outlined in Table 21. We have taken

[2] https://ghgprotocol.org/corporate-value-chain-scope-3-standard

this approach to maintain consistency with other GHG calculators in the Australian agricultural landscape. Expansion of the production boundary and inclusions of additional emissions sources may be considered in the future should standards be defined that require these inclusions.

Table 21. Scope 3 – inclusions and exclusions

Location	GHG Protocol Scope 3 Category	Status for NCA inclusion	Relevance assumptions for NCA
Pre-farm (upstream)	1 Purchased Goods & Services	Partially included	Inclusions: sheep and cattle purchases, synthetic fertiliser, superphosphate, urea, feed (grain, hay/silage, lucerne). This is expected to cover the vast majority of Category 1 Scope 3 emissions. Exclusions: all other emissions generating purchases (e.g., other inputs, white collar services, IT software etc).
	2 Capital Goods	Excluded	Emissions embodied in asset purchases, materials, and infrastructure.
	3 Upstream fuel and energy	Included	Electricity transmission losses and upstream fuel processing.
	4 Upstream transport	Partially included	Delivery from suppliers to the point of sale. Included are all inputs covered in Category 1 above, all other purchases are excluded.
	5 Waste from operations	Excluded	Emissions from waste generated on farm
	6 Business travel	Excluded	
	7 Employee commuting	Excluded	Including employees personal vehicles and or public transport (where relevant).
	8 Upstream leased assets	N/A	N/A unless the farm operates (not owns) leased assets not already accounted for in Scope 1 emissions
Post-farm (downstream)	9 Downstream transport	Partially included	Emissions associated with fuel use by farm vehicles for operational purposes are included. All other downstream transport of products excluded.
	10 Processing of sold products	Excluded	
	11 Use of sold products	Excluded	
	12. Waste from sold products	Excluded	
	13 Downstream leased assets	N/A	N/A – unless the farm sells agistment services to external parties, in which case the emissions associated with the livestock are included in scope 1 emissions calculations.
	14 Franchises	N/A	
	15 Investments	N/A	

5.1.4 Calculation of water use

Water consumption for livestock was calculated based on livestock numbers together with localised climate factors (Luke 1987). Spatial means of the seasonal maximum temperature data for these calculations were derived from the ANUClimate_v2.0 dataset (Hutchinson et al. 2021).

Water applied as irrigation of crops and pastures was collected as part of the farm production dataset and was allocated to the various farming enterprises as described in section 5.1.8.

A water-stress index (WSI) was derived for each farm (Pfister et al. 2009) and was applied to both the livestock water consumption and irrigation water use, with the normalised stress-weighted water use calculated using the worldwide WSI of 0.602 (Ridoutt and Pfister 2013).

5.1.5 Calculation of water pollution

Water pollution as a result of nitrogen leaching and run-off from animal manure and applied N-based fertiliser was calculated using methods outlined in National Inventory Report 2020 (DISER 2022), with the metric relating to the amount of nitrogen (kg) leaching or running-off from the agricultural landscape.

5.1.6 Calculation of waste

Waste generated from farming operations was estimated as the total non-biodegradable packaging waste from inputs that was not recycled. Factors for the waste associated with the packaging are provided in Table 22.

Table 22. Emission factors for pre-farm inputs

Pre-farm input	Kg Waste	Comment
Bulk fertiliser	N/A	No packaging
Bulka-bag packed input	0.00134 kg per kg of input	Assume no recycling
Bag (10-40kg) packed input	0.02 kg per kg input	Assume no recycling
IBC (liquid input)	0	Assume IBC recycled
Drum (10-25lt)	0.1 kg per litre input	Assume not recycled
Drum (Drum muster)	0	Recycled using the drum muster program
Hay/Lucerne bales	0.004 kg per kg input	2kg wrapping for 500 kg bale
Silage bales	0.0033 kg per kg input	2kg wrapping for 600 kg bale
Grain and concentrates	0	Assumed bulk delivery

5.1.7 Calculation of livestock and cropping rainfall use efficiency

The livestock rainfall use efficiency is calculated as:

Livestock Rainfall Efficiency = Total DSE / Total Grazing area * (5-year annual average rainfall / 100)

The Total DSE figure is calculated as the average daily dry matter consumed by the livestock, and this is derived during the emissions calculations using the methods described in Section 5.1.1.

Total grazing area is derived from the Ecosystem Asset Register (Section 2.6) for all units that have a grazing classification. This will exclude infrastructure, conservation and cropping areas (non-forage crops).

The annual rainfall is calculated as a spatial mean (within the farm boundary) of rainfall using the monthly rainfall data provided by the Australian Water Outlook dataset (Bureau of Meteorology 2023).

5.1.8 Allocation of resource use and pollution externalities to different farm products

The environmental performance metrics included in the reports provide metrics per unit of output for a range of products generated by the farm:

- Wool (kg)
- Sheep liveweight (kg)
- Cattle liveweight (kg)
- Sheep agistment $
- Cattle agistment $
- Crop (Tonnes)

The resource use and pollution metrics are generated for the whole of farm and then allocated to the products through a combination of allocation metrics provided by the farmer and derived metrics generated from the production data as shown in Figure 16.

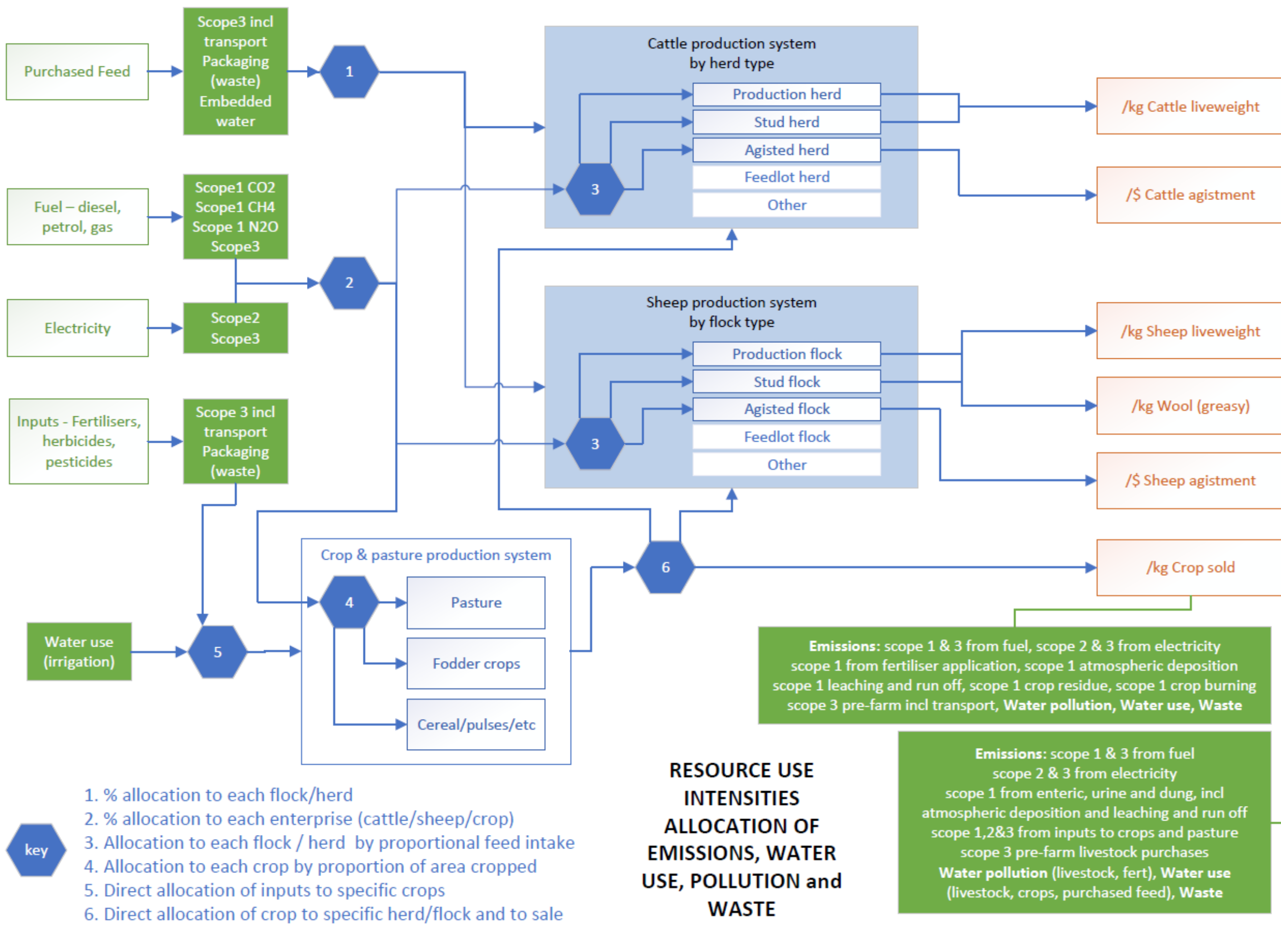

Figure 16. Schematic for the allocation of resource use and pollution to the farm product outputs.

The proportional allocation steps 1 and 2 in Figure 16 were provided by the farmer as part of the farm data collection process. Allocation step 3 was calculated using the proportion of dry matter consumed by each flock and herd (an intermediate metrics in the emissions calculations using the methods described in Section 5.1.1). Allocation step 4 was calculated based on the areas cropped of each crop type. Allocation of irrigation water and fertilisers impacts were assigned directly to each crop (which includes pastures, fodder crops and cereal crops).

The resulting crop resource use and pollution metrics were then split between the cropping enterprise and the livestock enterprises based on the proportional allocation of each crop to each of the flocks and herds (provided by the farmer or derived from the dry matter consumption in the case of the pasture systems).

In the case of a sheep operation where both wool and liveweight are produced, the resource use and pollution metrics are allocated to the wool and liveweight product groups through biophysical allocation (Wiedemann et al. 2015). A rolling 5-year average was calculated for the biophysical allocation to avoid the scenario of the allocation proportion being skewed by the timing of shearing and livestock sale events.

6 Quantification of Indices

This section outlines three indices that were calculated for the farm in its entirety: ecological condition, riparian buffer and proximity. They represent emergent properties of the farm and are complementary to the accounts described above. These Indices headline our Natural Capital Dashboard.

6.1 Ecological Condition

An important aspect of natural capital is the degree of ecological modification of a particular parcel of land from its 'natural' or 'reference' condition. For example, a grassy woodland that retains its tree canopy layer, shrub layer and a high proportion of native grasses and forbs in the ground layer has been modified substantially less (i.e., retains higher ecological condition) than a grassy woodland that has had its tree canopy cleared, and the native ground layer replaced with introduced grasses. This is irrespective of land use – both parcels of grassy woodland may be used for grazing. This concept is analogous to that of 'ecosystem' or 'vegetation condition' but is operationalised via the State and Transition models that classify discrete parcels of land into mutually exclusive Ecosystem States. To generate a whole of farm measure of ecological condition, we apply weightings to each Ecosystem State that represent its 'departure from reference condition'.

Ecological condition will influence the extent to which a parcel of land contributes to the flow of virtually all ecosystem services but is particularly relevant to Supporting and Cultural ecosystem services, such as habitat for species (biodiversity) and maintenance of genetic diversity. It is well established that the amount (extent) of habitat in a landscape is the single most important factor affecting the diversity and abundance of native species in a landscape. Translated to a farm-scale, this equates to the area of habitat (native ecosystems) retained on a farm. However, given the variation in condition of native ecosystems on farms, allocating patches of vegetation that contribute to habitat for biodiversity is vexed, precluding an absolute measure of habitat extent. However, Ecological Condition is a useful surrogate for habitat extent – farms with higher values of Ecological Condition are likely to have a greater proportion of habitat (i.e., extent) than farms with lower values of Ecological Condition.

The nature of the relationship between Ecological Condition and flow of ecosystem services is likely to differ between services. An important point is that we are not making an *a priori* judgement on the *value* of parcels of land based on Ecological Condition (i.e., higher is not necessarily "better"). Rather, the value to the farmer will depend on the intended purpose of that land and any trade-offs between different ecosystem services that are inherent in that land use and management. For example, grassy woodland with high Ecological Condition may contribute significantly to the flow of ecosystem services such as habitat for species, carbon sequestration, pollination and shelter for livestock but only moderately to provision of forage for livestock. In contrast, an intensively managed exotic pasture with low Ecological Condition may contribute significantly to the provision of forage for livestock but only marginally, if at all, to provision of habitat for native species. It is up to the farmer to determine the balance of land uses on their farm necessary to achieve their business, production, lifestyle and environmental goals.

6.1.1 Method of calculation

Ecological Condition is an area-weighted measure that captures the overall level of ecological condition of a farm. All parts of the farm are included in the calculation. The first step involves assigning a weighting to every Ecosystem State in the State and Transition models (see Table 23 for weightings and Appendix A for State and Transition models). The weighting represents the degree of modification for a particular Ecosystem State, from 1 (reference condition that retains full ecological integrity) to 0 (completely modified). Ecological Condition of a farm is then calculated as area-weighted sum of the extent (area) of all Ecosystem States present on the farm, divided by the total area of the farm:

Ecological Condition = $\sum_{i}^{k} Ai * Wi$ / Total area of farm

where *Ai* is the total area of Ecosystem State *i* and *Wi* is the assigned condition weighting for Ecosystem State *i* (Table 23) for all *k* ecosystem condition states present on a farm.

Ecological Condition is a unitless index, that will be a continuous variable from 0 to 1.

Table 23. Integrity weighting for ecosystem condition states. (t) denotes presence of scattered mature paddock trees. (i) denotes irrigation. + denotes mature remnant trees in planting.

Natural Capital Asset	Ecosystem Type	Ecosystem State	Condition weighting
Native ecosystems	**Forest**	RF	1
		TF1	0.9
		TF2	0.8
		TF3	0.6
		TF4	0.4
		TF5	0.5
		TF6	0.4
	Woodland	RW	1
		TW1	0.9
		TW2	0.8
		TW3	0.6
		TW4	0.4
		TW5	0.5
		TW6	0.4
		DW1	0.5
		DW2	0.4
		DW3	0.3
		DW4	0.2
		DW5	0.3
		DW6	0.2
	Shrubland	RS	1
		TS1	0.9
		TS2	0.8
		TS3	0.6
		TS4	0.4
		DS1	0.5
		DS2	0.4
		DS3	0.3
		DS4	0.2
	Grassland	RG	1
		MG1	0.9
		MG1(t)	0.9
		MG2	0.8
		MG2(t)	0.8
		MG3	0.6
		MG3(t)	0.6
Intensive land-use		MG4	0.4

		MG4(t)	0.4
		MG5	0.1
		MG5(t)	0.1
		MG5(i)	0.1
		MG6	0.1
		MG6(t)	0.1
		MG6(i)	0.1
		DG1	0.5
		DG1(t)	0.6
		DG2	0.4
Native ecosystems		DG2(t)	0.5
		DG3	0.3
		DG3(t)	0.4
	Pasture	DG4	0.2
		DG4(t)	0.3
		DG5	0.1
Intensive land-use		DG5(t)	0.2
		DG5(i)	0.1
		DG6	0.1
		DG6(t)	0.2
		DG6(i)	0.1
		PNT1	0.15
		PNT1+	0.25
		PNT2	0.4
		PNT2+	0.5
		PNT3	0.6
Planted vegetation		PNT3+	0.7
	Planted vegetation	PNT4	0.5
		PNT4+	0.6
		PNS1	0.2
		PNS2	0.4
		EWV1	0.1
		EWV2	0.1
		EWV3	0.05
Intensive land-use		C1	0.15
	Cropland	C2	0.05
		C3	0.05
	Infrastructure		0

6.2 Riparian Buffer Score

Water quality (i.e., purity, amount) is difficult to measure directly from remote sources and may be disproportionately influenced by external (off-farm) inputs (e.g. sediment loads from upstream, run-off from neighbouring properties). While multiple factors contribute to water quality, such as ground cover (see Section 4.2) and chemical inputs (e.g., fertilisers, pesticides), the extent to which natural and artificial water bodies are fringed by vegetation plays a critical role in water quality. Moreover, riparian (streamside) vegetation is disproportionately important in agricultural landscapes, providing refuge and habitat for species (Bennett et al. 2014), filtering surface flows for regulation of water flow and provision of freshwater (downstream), and capturing carbon for sequestration and storage (as riparian areas are in more productive areas, they capture and store more carbon than surrounding areas). Riparian areas are usually linear, potentially increasing structural connectivity on farms and in landscapes. Therefore, the extent to which riparian areas retain native vegetation (or are replanted) is a useful indicator for multiple values (e.g., habitat, water quality, connectivity, flow regulation). This is captured in the Riparian Buffer Score, which is the proportion of the riparian zone that has tree canopy cover.

The riparian zone is the area between the waterline of a waterway and the top of the bank or the transition to upland vegetation. The width of the riparian zone varies with the morphology of the waterway and the topography of the landscape and is generally between 10-30 metres, but in landscapes with low relief it can extend for hundreds of metres.

6.2.1 Method of calculation

The Riparian Buffer Score is calculated as the proportion of riparian areas (along creeks, streams and rivers) that retain their tree cover. For the purposes of generating this index, riparian areas are classified as mapped (named) creeks, streams and rivers on a farm, or areas that are clearly identifiable as riparian from remote sensing or aerial imagery. The riparian buffer score is calculated as the total area of riparian canopy cover divided by the total area of riparian zone, where the riparian zone is defined as a 50m buffer either side of major waterways (rivers) and 30m either side of minor waterways (creeks).

Riparian Buffer Score is a continuous variable from 0 (no canopy cover in the riparian zone) to 1 (complete canopy cover in the riparian zone). Canopy cover includes native and exotic, and remnant and replanted woody vegetation. Where the farm boundary coincides with a waterway, only the riparian zone on the farm is included in the calculation. Where the waterway runs through a natural grassland, we would not expect the riparian zone to have canopy cover. This will result in an underestimate of the true riparian condition. Farms with no riparian areas would not be scored for this index.

Riparian Buffer Score = (total area of riparian zone canopy cover)/(total area of riparian zone)

6.3 Proximity

Proximity captures the average distance of all production areas on the farm to wooded vegetation (native and exotic, planted and remnant). This metric will influence the likelihood and quality of some regulating ecosystem services received by production areas. For example, to receive micro-climate regulation benefits (e.g., shade, wind-reduction), the production land must be relatively close to wooded vegetation. Similarly, the extent of pollination and pest-suppression services delivered by beneficial invertebrates will be influenced the proximity of production areas to natural habitat (in combination with Ecological Condition).

Proximity measures how close, on average, production areas are to wooded vegetation. All wooded vegetation (native and exotic, planted and remnant) that is captured by remote sensed imagery as canopy cover will be included in calculation of Proximity. It is calculated as the mean distance (*d*) from each pixel in the 'production' areas of a farm to the nearest wooded vegetation pixel (located either within or outside production areas).

The first step in the calculation of Proximity is to nominate which pixels are to be included in the 'production areas' on the farm. To do this, all ecosystem assets with production nominated as the primary or secondary purpose are identified. Areas of farm infrastructure (e.g., sheds, houses) are not included. Canopy cover is cropped to a 500 m buffer to include the contribution of areas of wooded vegetation beyond the farm boundary (i.e., on roadsides or neighbouring properties) in the calculation of *d*. Cells adjacent to tree cells are assigned the maximum obtainable value (*d* = 10). Treed cells are also given a value of 10 so as not to penalise farms based on their distribution of trees. The value, *d*, is then scaled to generate a value between 0 and 1 by calculating a ratio between 10 and the distance to the nearest tree for each cell (i.e. *d*' = 10/*d*; Figure 17). Proximity for the farm is then calculated as the mean of *d*' across all production cells.

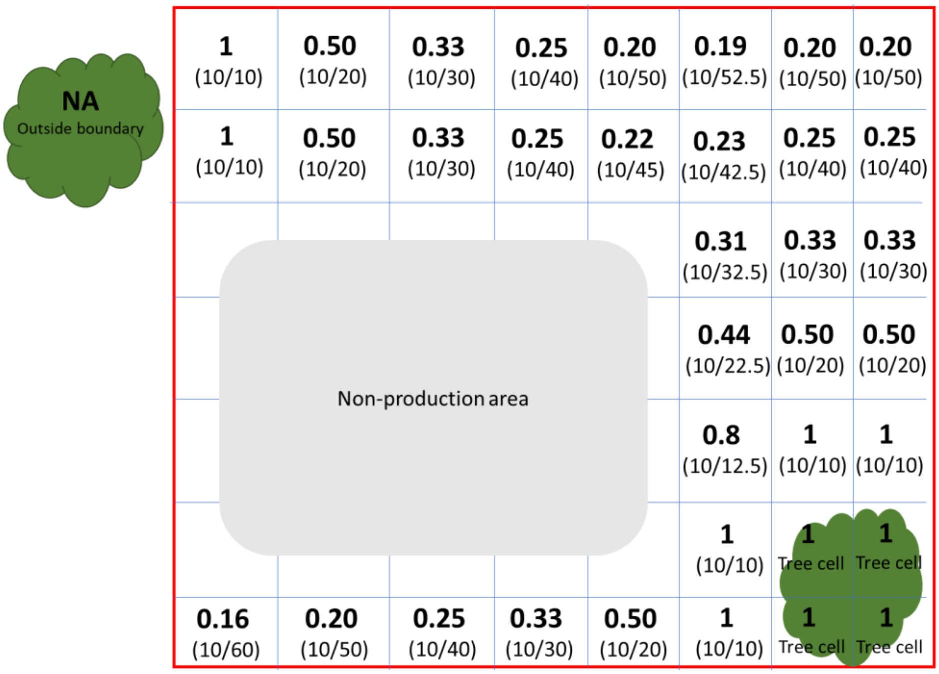

Figure 17. Conceptual diagram for Proximity. For each production cell, the distance to the nearest tree is calculated. All trees within a 500 m radius of the property are included. A ratio 10/distance is used to standardise the distance number between 0-1. Proximity is the mean across all production cells.

Proximity is a unitless index, that will be a continuous variable from 0 to 1. Proximity approaches 1 when all production areas are within 10 m of wooded vegetation. Proximity values of 0.5 indicate production areas are on average 20 m from wooded vegetation; values of 0.2 are on average 50 m from wooded vegetation; values of 0.1 are on average 100 m from wooded vegetation. Values approaching 0 represent farms in which all production areas are distant from woody vegetation. Proximity can be mapped across the farm based on the values for each cell (Figure 18).

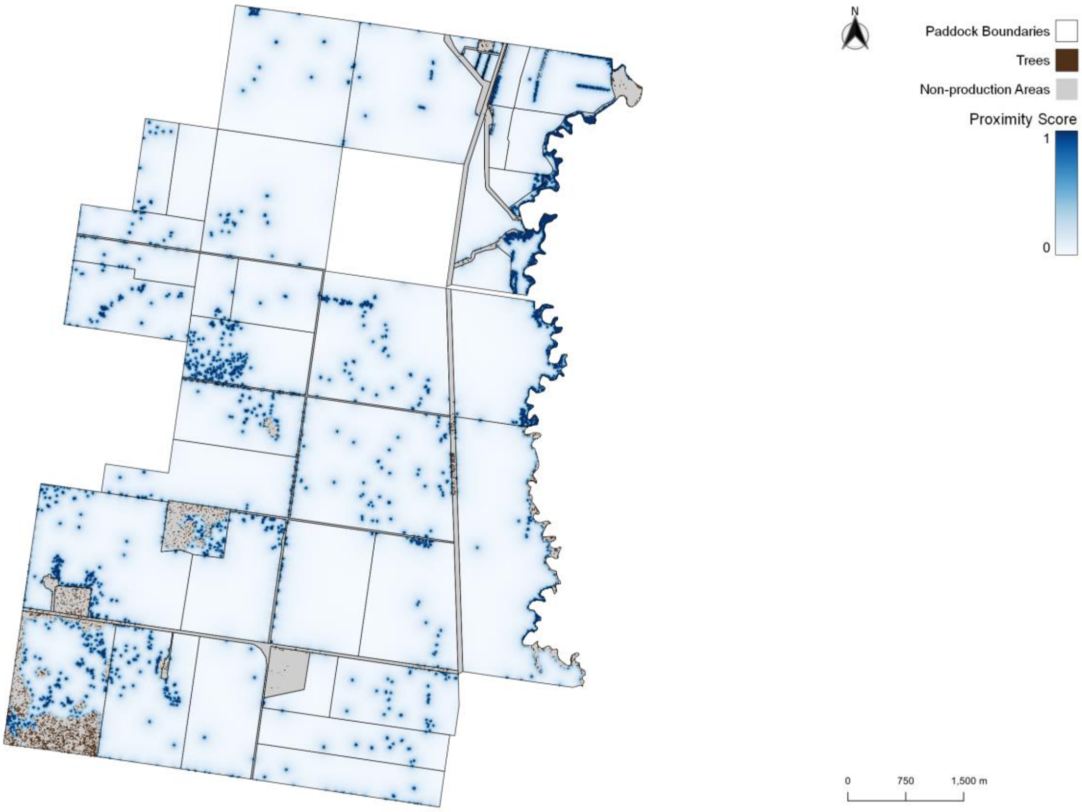

Figure 18. Example map of Proximity across a farm.

7 Further Information

7.1 Supplementary Materials

Table 24 lists a range of supplementary documents and materials that support this Blueprint. These are all available from the project team upon request. These materials can be used to provide further information about the conceptual framing and data collection methods.

Table 24: Supplementary material for further information about the methods used to quantify natural capital in the Farm-scale Natural Capital Accounting project.

Document Name	Authors	Comment
Orana Farm-scale Natural Capital Account 2022. La Trobe University and Integrated Futures.	Danny O'Brien, Angela Hawdon, Rachel Lawrence, Alex Maisey, Sue Ogilvy, Fred Rainsford, Imogen Semmler, Grace Sutton, and Jim Radford.	Example account with full documentation of tables and figures.
Towards aggregation of Farm-scale Natural Capital Accounts to SEEA	Sue Ogilvy, Danny O'Brien	Proposes an approach to the use of farm-scale natural capital accounts in preparation of national and sub-national accounts prepared according to the SEEA EA.
Natural Capital Ecological Assessment Standard Operating Procedure_v11	Imogen Semmler, Rachel Lawrence, Jim Radford, Danny O'Brien, Fred Rainsford, Matt Appleby and Sue Ogilvy.	Detailed protocols for rapid ecological assessment data collection.
State and Transition Model Decision Tree	Jim Radford, Fred Rainsford, Alex Maisey	Decision tree for use in the field to assign an Ecosystem Unit to an Ecosystem State.
R codes and RDA models	Fred Rainsford, Alex Maisey, Grace Sutton	Various models used for generating predictions of bird and plant species richness, and arthropod-mediated ecosystem services; and calculating shade, shelter, proximity and riparian buffer indices.
Forage condition scoring materials	Danny O'Brien, Rachel Lawrence, Imogen Semmler	Lookup tables for the species categorisation, density weightings and thresholds for forage classification.

7.2 Contacts

For further information or to obtain materials listed in Table 24, please contact:

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Appendix A: State and transition models used in the FsNCA project

A.1 Forest State and Transition Model

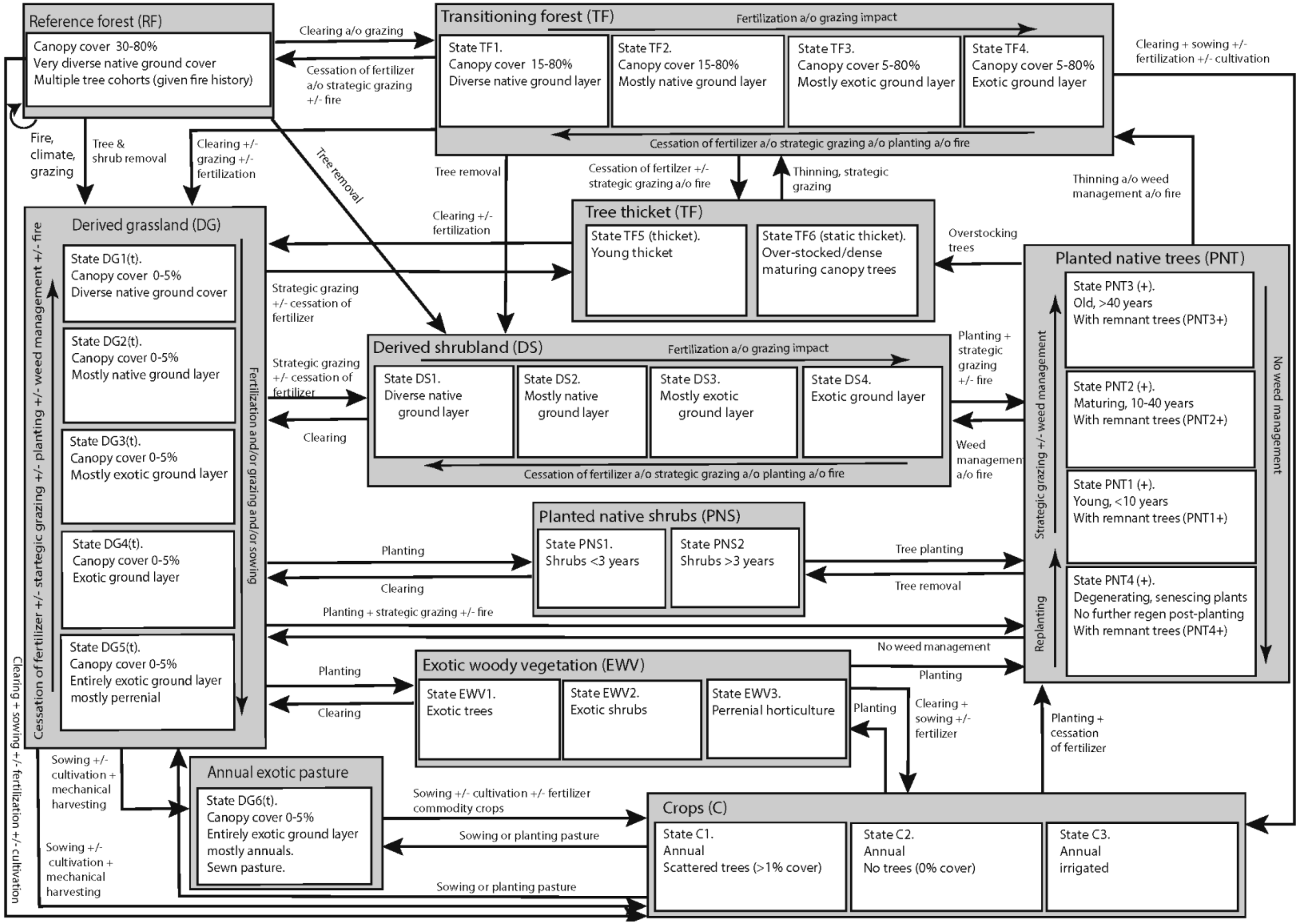

Table A1. Thresholds for Forest State and Transition Model.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
RF	Reference forest	15-80	0-100	>90	>50	Species richness >85% relative to local benchmark. A 'stable state' maintained by fire and/or grazing and/or drought climate processes. Very high diversity relative to benchmark. Evidence of regeneration, multiple age cohorts of canopy trees. Very little, if any, exotic species. Represents 'best available' condition.
TF1	Transitioning forest 1	15-80	0-100	71-90	>50	Relatively intact forests with high native diversity. Some degradation of canopy layer and understorey diversity relative to reference condition.
TF2	Transitioning forest 2	15-80	0-100	41-70 (>70 if exotic shrub cover >10)	>30	Mostly native understorey with potentially degradation of the canopy layer and understorey diversity. There may be exotic shrubs present.
TF3	Transitioning forest 3	5-80	0-100	11-40 (>40 if exotic shrub cover >30)	>10	Mostly exotic ground layer with few native species present. Some evidence of canopy regeneration – potentially more in mesic areas.
TF4	Transitioning forest 4	5-80	0-100	0-10	n/a	Ground layer vegetation almost entirely exotic. Some evidence of canopy regeneration – potentially more in mesic areas.
TF5	Transitioning forest 5	>5	<10	n/a	>10	Dense thicket of regenerating canopy trees, often occurring in patches.
TF6	Transitioning forest 6	>5	<10	n/a	>10	'Static' thicket. High density of sub-mature canopy trees. Tree height is less than the maximum expected for the vegetation type.
DG1(t)	Derived grassland 1(t)	0-5	<10	>70	>50	High diversity of native species in the ground layer. Few, if any, exotic species. If scattered trees present, then DG1t.
DG2(t)	Derived grassland 2(t)	0-5	<10	41-70	>50	Mostly native species in the ground layer. Some exotic species. If scattered trees present, then DG2t.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
DG3(t)	Derived grassland 3(t)	0-5	<10	11-40	>30	Mostly exotic species in the ground layer. Few native species. If scattered trees present, then DG3t.
DG4(t)	Derived grassland 4(t)	0-5	<10	1-10	1-30	Exotic ground layer. Few native species may be present. If scattered trees present, then DG4t.
DG5(t)	Derived grassland 5(t)	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by perennial species. Depending on time of year, may have annual dominance but with a perennial base. If scattered trees present, then DG5t.
DG6(t)	Derived grassland 6(t). Annual sewn pasture.	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by annual species. If scattered trees present, then DG6t. Can be a forage crop, grazed or harvested.
DS1	Derived shrubland 1	0-5	>10	>70	>50	Native shrubs (not planted) with ground layer equivalent to DG1.
DS2	Derived shrubland 2	0-5	>10	41-70 (>70 if exotic shrub cover >10)	>30	Native shrubs (not planted) with ground layer equivalent to DG2.
DS2	Derived shrubland 3	0-5	>10	11-40 (>40 if exotic shrub cover >30)	>10	Native shrubs (not planted) with ground layer equivalent to DG3.
DS3	Derived shrubland 4	0-5	>10	0-10	n/a	Native shrubs (not planted) with ground layer equivalent to DG4.
PNT1(+)	Planted native trees 1	n/a	n/a	n/a	n/a	Young planted native trees (<10 years). If scattered trees present, then PNT1+.
PNT2(+)	Planted native trees 2	>5	n/a	n/a	n/a	Maturing planted native trees (10 – 40 years). If scattered trees present, then PNT1+.
PNT3(+)	Planted native trees 3	>5	n/a	n/a	n/a	Old, planted trees (>40 years). If scattered trees present, then PNT1+.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
PNT4(+)	Planted native trees 4	n/a	n/a	n/a	n/a	Senescing planted trees. If scattered trees present, then PNT1+.
PNS1	Planted native shrubs 1	<5	>0	n/a	n/a	Young planted native shrubs (<3 years).
PNS2	Planted native shrubs 2	<5	>0	n/a	n/a	Mature planted native shrubs (>=3 years).
EWV1	Exotic woody vegetation 1	>5	n/a	n/a	<70	Exotic trees. May be planted or self-seeded.
EWV2	Exotic woody vegetation 2	0-5	>10	n/a	n/a	Exotic shrubs. May be planted or self-seeded.
EWV3	Exotic woody vegetation 3	n/a	n/a	n/a	n/a	Perennial horticulture.
C1	Crops 1	>0	n/a	n/a	n/a	Annual crops with scattered trees.
C2	Crops 2	0	n/a	n/a	n/a	Annual crops without scattered trees.
C3	Crops 3	0	n/a	n/a	n/a	Irrigated annual crops.

A.2 Grassland State and Transition Model

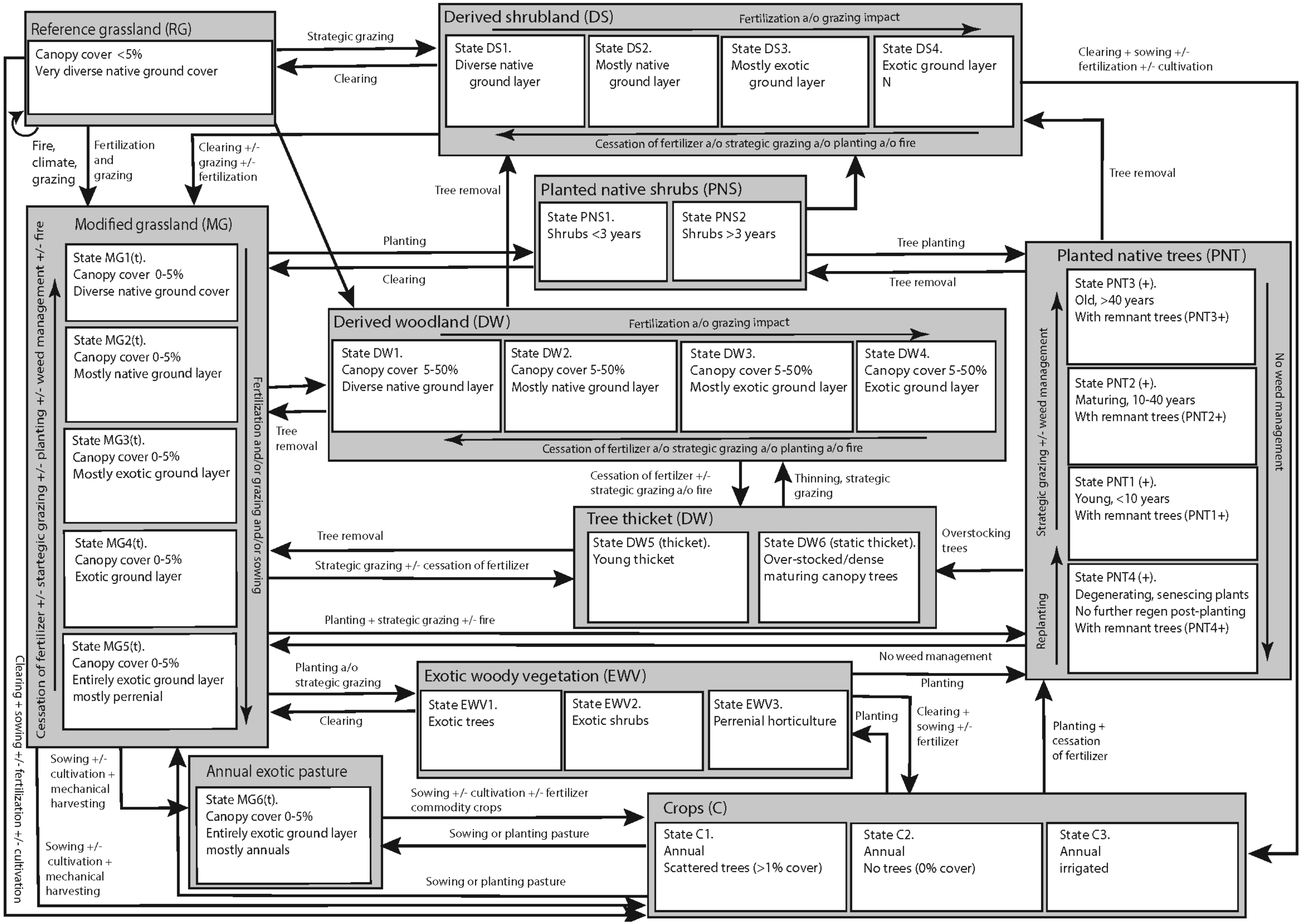

Table A2. Thresholds for Grasslands State and Transition Model.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
RG	Reference grassland	0-5	<10	>90	>50	Species richness >85% relative to local benchmark. A ‘stable state’ maintained by fire and/or grazing and/or drought climate processes. Very high diversity relative to benchmark. Evidence of regeneration. Very little, if any, exotic species. Represents ‘best available’ condition.
MG1(t)	Modified grassland 1(t)	0-5	<10	71-90	>50	High diversity of native species in the ground layer. Few, if any, exotic species. If scattered trees present, then MG1t.
MG2(t)	Modified grassland 2(t)	0-5	<10	41-70	>50	Mostly native species in the ground layer. Some exotic species. If scattered trees present, then MG2t.
MG3(t)	Modified grassland 3(t)	0-5	<10	11-40	>30	Mostly exotic species in the ground layer. Few native species. If scattered trees present, then MG3t.
MG4(t)	Modified grassland 4(t)	0-5	<10	0-10	1-30	Exotic ground layer. Few native species may be present. If scattered trees present, then MG4t.
MG5(t)	Modified grassland 5(t)	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by perennial species. Depending on time of year, may have annual dominance but with a perennial base. If scattered trees present, then DG5t
MG6(t)	Modified grassland 6(t)	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by annual species. If scattered trees present, then DG6t. Can be a forage crop, grazed or harvested.If scattered trees present, then MG5t.
DW1	Derived woodland 1	15-80	0-100	>70	>50	Woodland with high native diversity. Some degradation of canopy layer and understorey diversity relative to reference condition.
DW2	Derived woodland 2	15-80	0-100	41-70 (>70 if exotic shrub cover >10)	>30	Mostly native understorey with potentially degradation of the canopy layer and understorey diversity. There may be exotic shrubs present.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
DW3	Derived woodland 3	5-80	0-100	11-40 (>40 if exotic shrub cover >30)	>10	Mostly exotic ground layer with few native species present. Some evidence of canopy regeneration – potentially more in mesic areas.
DW4	Derived woodland 4	5-80	0-100	0-10	n/a	Ground layer vegetation almost entirely exotic. Some evidence of canopy regeneration – potentially more in mesic areas.
DW5	Derived woodland 5	>5	<10	n/a	>10	Dense thicket of regenerating canopy trees, often occurring in patches.
DW6	Derived woodland 6	>5	<10	n/a	>10	'Static' thicket. High density of sub-mature canopy trees. Tree height is less than the maximum expected for the vegetation type.
DS1	Derived shrubland 1	0-5	>10	>70	>50	Native shrubs (not planted) with ground layer equivalent to DG1.
DS2	Derived shrubland 2	0-5	>10	41-70 (>70 if exotic shrub cover >10)	>30	Native shrubs (not planted) with ground layer equivalent to DG2.
DS2	Derived shrubland 3	0-5	>10	11-40 (>40 if exotic shrub cover >30)	>10	Native shrubs (not planted) with ground layer equivalent to DG3.
DS3	Derived shrubland 4	0-5	>10	0-10	n/a	Native shrubs (not planted) with ground layer equivalent to DG4.
PNT1(+)	Planted native trees 1	n/a	n/a	n/a	n/a	Young planted native trees (<10 years). If scattered trees present, then PNT1+.
PNT2(+)	Planted native trees 2	>5	n/a	n/a	n/a	Maturing planted native trees (10 – 40 years). If scattered trees present, then PNT1+.
PNT3(+)	Planted native trees 3	>5	n/a	n/a	n/a	Old, planted trees (>40 years). If scattered trees present, then PNT1+.
PNT4(+)	Planted native trees 4	n/a	n/a	n/a	n/a	Senescing planted trees. If scattered trees present, then PNT1+.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
PNS1	Planted native shrubs 1	<5	>0	n/a	n/a	Young planted native shrubs (<3 years).
PNS2	Planted native shrubs 2	<5	>0	n/a	n/a	Mature planted native shrubs (>=3 years).
EWV1	Exotic woody vegetation 1	>5	n/a	n/a	<70	Exotic trees. May be planted or self-seeded.
EWV2	Exotic woody vegetation 2	0-5	>10	n/a	n/a	Exotic shrubs. May be planted or self-seeded.
EWV3	Exotic woody vegetation 3	n/a	n/a	n/a	n/a	Perennial horticulture.
C1	Crops 1	>0	n/a	n/a	n/a	Annual crops with scattered trees.
C2	Crops 2	0	n/a	n/a	n/a	Annual crops without scattered trees.
C3	Crops 3	0	n/a	n/a	n/a	Irrigated annual crops.

A.3 Shrubland State and Transition Model

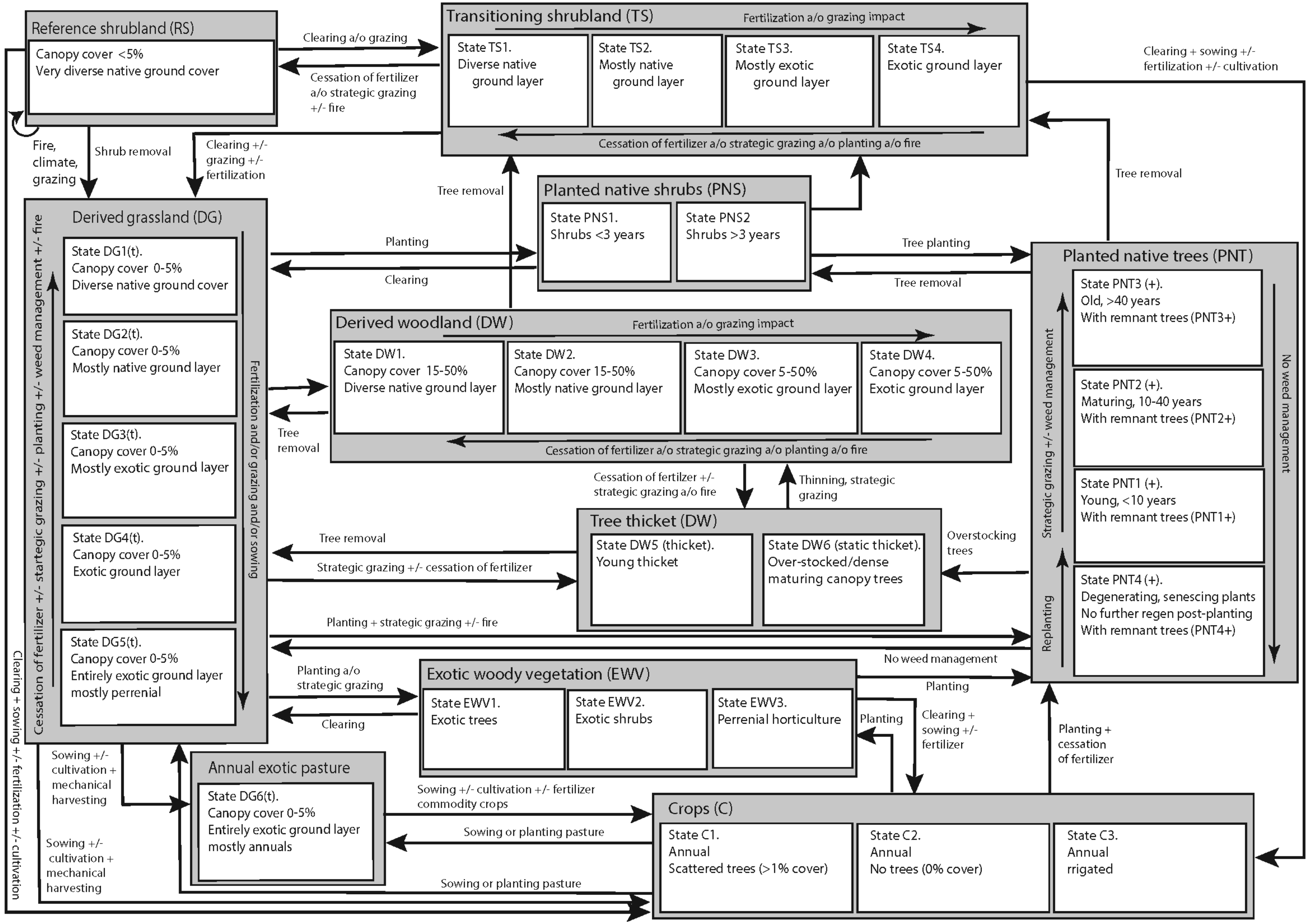

Table A3. Thresholds for Shrubland State and Transition Model.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
RS	Reference shrubland	0-5	>10	>90	>50	Species richness >85% relative to local benchmark. A ‘stable state’ maintained by fire and/or grazing and/or drought climate processes. Very high diversity relative to benchmark. Evidence of regeneration. Very little, if any, exotic species. Represents ‘best available’ condition.
TS1	Transitioning shrubland 1	0-5	>10	71-90	>50	Native shrubs (not planted) with ground layer equivalent to DG1.
TS2	Transitioning shrubland 2	0-5	>10	41-70 (>70 if exotic shrub cover >10)	>30	Native shrubs (not planted) with ground layer equivalent to DG2.
TS3	Transitioning shrubland 3	0-5	>10	11-40 (>40 if exotic shrub cover >30)	>10	Native shrubs (not planted) with ground layer equivalent to DG3.
TS3	Transitioning shrubland 4	0-5	>10	0-10	n/a	Native shrubs (not planted) with ground layer equivalent to DG4.
DW1	Derived woodland 1	15-80	0-100	>70	>50	Woodland with high native diversity. Some degradation of canopy layer and understorey diversity relative to reference condition.
DW2	Derived woodland 2	15-80	0-100	41-70 (>70 if exotic shrub cover >10)	>30	Mostly native understorey with potentially degradation of the canopy layer and understorey diversity. There may be exotic shrubs present.
DW3	Derived woodland 3	5-80	0-100	11-40 (>40 if exotic shrub cover >30)	>10	Mostly exotic ground layer with few native species present. Some evidence of canopy regeneration – potentially more in mesic areas.
DW4	Derived woodland 4	5-80	0-100	0-10	n/a	Ground layer vegetation almost entirely exotic. Some evidence of canopy regeneration – potentially more in mesic areas.
DW5	Derived woodland 5	>5	<10	0-100	>10	Dense thicket of regenerating canopy trees, often occurring in patches.
DW6	Derived woodland 6	>5	<10	0-100	>10	‘Static’ thicket. High density of sub-mature canopy trees. Tree height is less than the maximum expected for the vegetation type.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
DG1(t)	Derived grassland 1(t)	0-5	<10	>70	>50	High diversity of native species in the ground layer. Few, if any, exotic species. If scattered trees present, then DG1t.
DG2(t)	Derived grassland 2(t)	0-5	<10	41-70	>50	Mostly native species in the ground layer. Some exotic species. If scattered trees present, then DG2t.
DG3(t)	Derived grassland 3(t)	0-5	<10	11-40	>30	Mostly exotic species in the ground layer. Few native species. If scattered trees present, then DG3t.
DG4(t)	Derived grassland 4(t)	0-5	<10	0-10	1-30	Exotic ground layer. Few native species may be present. If scattered trees present, then DG4t.
DG5(t)	Derived grassland 5(t)	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by perennial species. Depending on time of year, may have annual dominance but with a perennial base. If scattered trees present, then DG5t.
DG6(t)	Derived grassland 6(t). Annual sewn pasture.	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by annual species. If scattered trees present, then DG6t. Can be a forage crop, grazed or harvested.
PNT1(+)	Planted native trees 1	n/a	n/a	n/a	n/a	Young planted native trees (<10 years). If scattered trees present, then PNT1+.
PNT2(+)	Planted native trees 2	>5	n/a	n/a	n/a	Maturing planted native trees (10 – 40 years). If scattered trees present, then PNT1+.
PNT3(+)	Planted native trees 3	>5	n/a	n/a	n/a	Old, planted trees (>40 years). If scattered trees present, then PNT1+.
PNT4(+)	Planted native trees 4	n/a	n/a	n/a	n/a	Senescing planted trees. If scattered trees present, then PNT1+.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
PNS1	Planted native shrubs 1	<5	>0	n/a	n/a	Young planted native shrubs (<3 years).
PNS2	Planted native shrubs 2	<5	>0	n/a	n/a	Mature planted native shrubs (>=3 years).
EWV1	Exotic woody vegetation 1	>5	n/a	n/a	<70	Exotic trees. May be planted or self-seeded.
EWV2	Exotic woody vegetation 2	0-5	>10	n/a	n/a	Exotic shrubs. May be planted or self-seeded.
EWV3	Exotic woody vegetation 3	n/a	n/a	n/a	n/a	Perennial horticulture.
C1	Crops 1	>0	n/a	n/a	n/a	Annual crops with scattered trees.
C2	Crops 2	0	n/a	n/a	n/a	Annual crops without scattered trees.
C3	Crops 3	0	n/a	n/a	n/a	Irrigated annual crops.

A.4 Woodland State and Transition Model

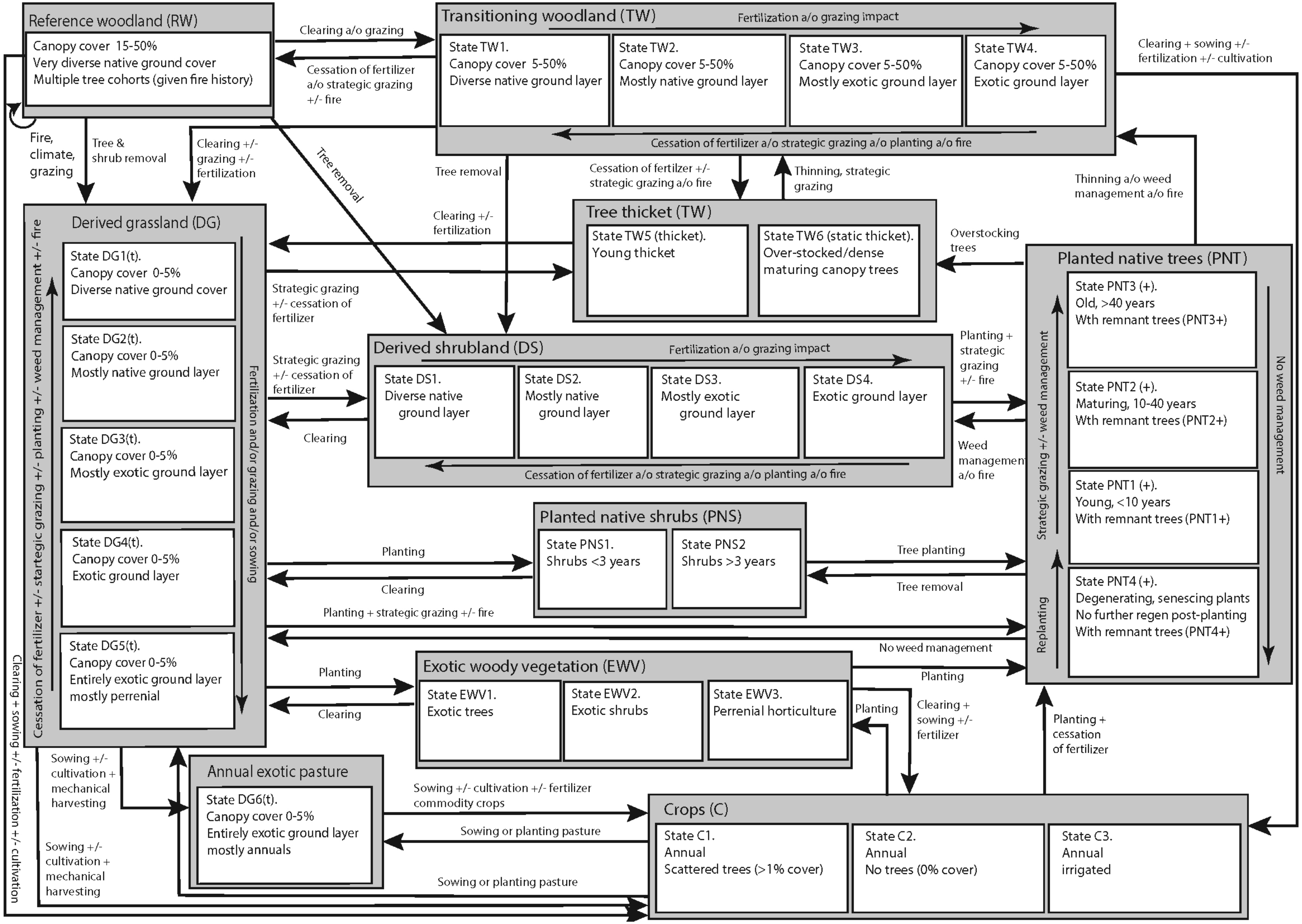

Table A4. Thresholds for Woodland State and Transition Model

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
RW	Reference woodland	15-50	<50	>90	>50	Species richness >85% relative to local benchmark. A 'stable state' maintained by fire and/or appropriate grazing and/or drought climate processes. Very high diversity relative to benchmark. Evidence of regeneration, multiple age cohorts of canopy trees. Very little, if any, exotic species. Represents 'best available' condition. In some low or very high productivity areas, RW (or TW1/2) states may naturally have canopy cover in the range of 5-15% but this needs to be accompanied by very high native species composition in the shrub and ground layers and the absence of tree clearing for many decades.
TW1	Transitioning woodland 1	15-50	0-100	71-90	>50	Relatively intact woodlands with high native diversity. Some degradation of canopy layer and understorey diversity relative to reference condition.
TW2	Transitioning woodland 2	15-50	0-100	41-70 (>70 if exotic shrub cover >10)	>30	Mostly native understorey with potentially degradation of the canopy layer and understorey diversity. There may be exotic shrubs present.
TW3	Transitioning woodland 3	5-50	0-100	11-40 (>50 if exotic shrub cover >30)	>10	Mostly exotic ground layer with few native species present. Some evidence of canopy regeneration – potentially more in mesic areas.
TW4	Transitioning woodland 4	5-50	0-100	0-10	n/a	Ground layer vegetation almost entirely exotic. Some evidence of canopy regeneration – potentially more in mesic areas.
TW5	Transitioning woodland 5	>5 (but with >50% cover of immature saplings)	<10	n/a	>10	Dense thicket of regenerating canopy trees, often occurring in patches.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
TW6	Transitioning woodland 6	>5 (but with >50% cover of sub-canopy trees)	<10	n/a	>10	'Static' thicket. High density of sub-mature canopy trees. Tree height is less than the maximum expected for the vegetation type.
DG1(t)	Derived grassland 1(t)	0-5	<10	>70	>50	High diversity of native species in the ground layer. Few, if any, exotic species. If scattered trees present, then DG1t.
DG2(t)	Derived grassland 2(t)	0-5	<10	41-70	>50	Mostly native species in the ground layer. Some exotic species. If scattered trees present, then DG2t.
DG3(t)	Derived grassland 3(t)	0-5	<10	11-40	>30	Mostly exotic species in the ground layer. Few native species. If scattered trees present, then DG3t.
DG4(t)	Derived grassland 4(t)	0-5	<10	1-10	1-30	Exotic ground layer. Few native species may be present. If scattered trees present, then DG4t.
DG5(t)	Derived grassland 5(t)	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by perennial species. Depending on time of year, may have annual dominance but with a perennial base. If scattered trees present, then DG5t.
DG6(t)	Derived grassland 6(t). Annual sewn pasture.	0-5	<10	n/a	<1	Entirely exotic ground layer dominated by annual species. If scattered trees present, then DG6t. Can be a forage crop, grazed or harvested.
DS1	Derived shrubland 1	0-5	>10	>60	>50	Native shrubs (not planted) with ground layer equivalent to DG1.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
DS2	Derived shrubland 2	0-5	>10	41-60 (>60 if exotic shrub cover >10)	>30	Native shrubs (not planted) with ground layer equivalent to DG2.
DS2	Derived shrubland 3	0-5	>10	11-40 (>50 if exotic shrub cover >30)	>10	Native shrubs (not planted) with ground layer equivalent to DG3.
DS3	Derived shrubland 4	0-5	>10	0-10	n/a	Native shrubs (not planted) with ground layer equivalent to DG4.
PNT1(+)	Planted native trees 1	n/a	n/a	n/a	n/a	Young planted native trees (<10 years). If scattered remnant trees present, then PNT1+.
PNT2(+)	Planted native trees 2	>5	n/a	n/a	n/a	Maturing planted native trees (10 – 40 years). If scattered remnant trees present, then PNT1+.
PNT3(+)	Planted native trees 3	>5	n/a	n/a	n/a	Old, planted trees (>40 years). If scattered remnant trees present, then PNT1+.
PNT4(+)	Planted native trees 4	n/a	n/a	n/a	n/a	Senescing planted trees (without regeneration). If scattered remnant trees present, then PNT1+.
PNS1	Planted native shrubs 1	<5	>0	n/a	n/a	Young planted native shrubs (<3 years).
PNS2	Planted native shrubs 2	<5	>0	n/a	n/a	Mature planted native shrubs (>=3 years).
EWV1	Exotic woody vegetation 1	>5	n/a	0-100	0-100	Exotic trees. May be planted or self-seeded.
EWV2	Exotic woody vegetation 2	0-5	>10	0-100	0-100	Exotic shrubs. May be planted or self-seeded.

Ecosystem State code	Ecosystem State name	Canopy cover - mature trees (%)	Shrub cover (%)	Native ground layer (% of composition)	Native ground layer (% cover)	Description
EWV3	Exotic woody vegetation 3	n/a	n/a	0-100	0-100	Perennial (woody) horticulture.
C1	Crops 1	>0	n/a	n/a	n/a	Dryland annual crops with scattered trees.
C2	Crops 2	0	n/a	n/a	n/a	Dryland annual crops without scattered trees.
C3	Crops 3	0	n/a	n/a	n/a	Irrigated annual crops.

Appendix B: Imputation log

Distribution of rapid ecological survey points (Figure B1) on example farm. Note that in the Natural Capital Account project, rapid ecological assessments were undertaken both as part of the Ecosystem Asset validation process and for the biodiversity surveys. Sometimes these points overlapped or were close to each other, resulting in multiple survey points per Ecosystem Unit or paddock (Figure B1). In total, 52 rapid ecological assessments across 29 Ecosystem Units were undertaken by trained field ecologists as part of the Farm-scale Natural Capital Accounts program on this farm.

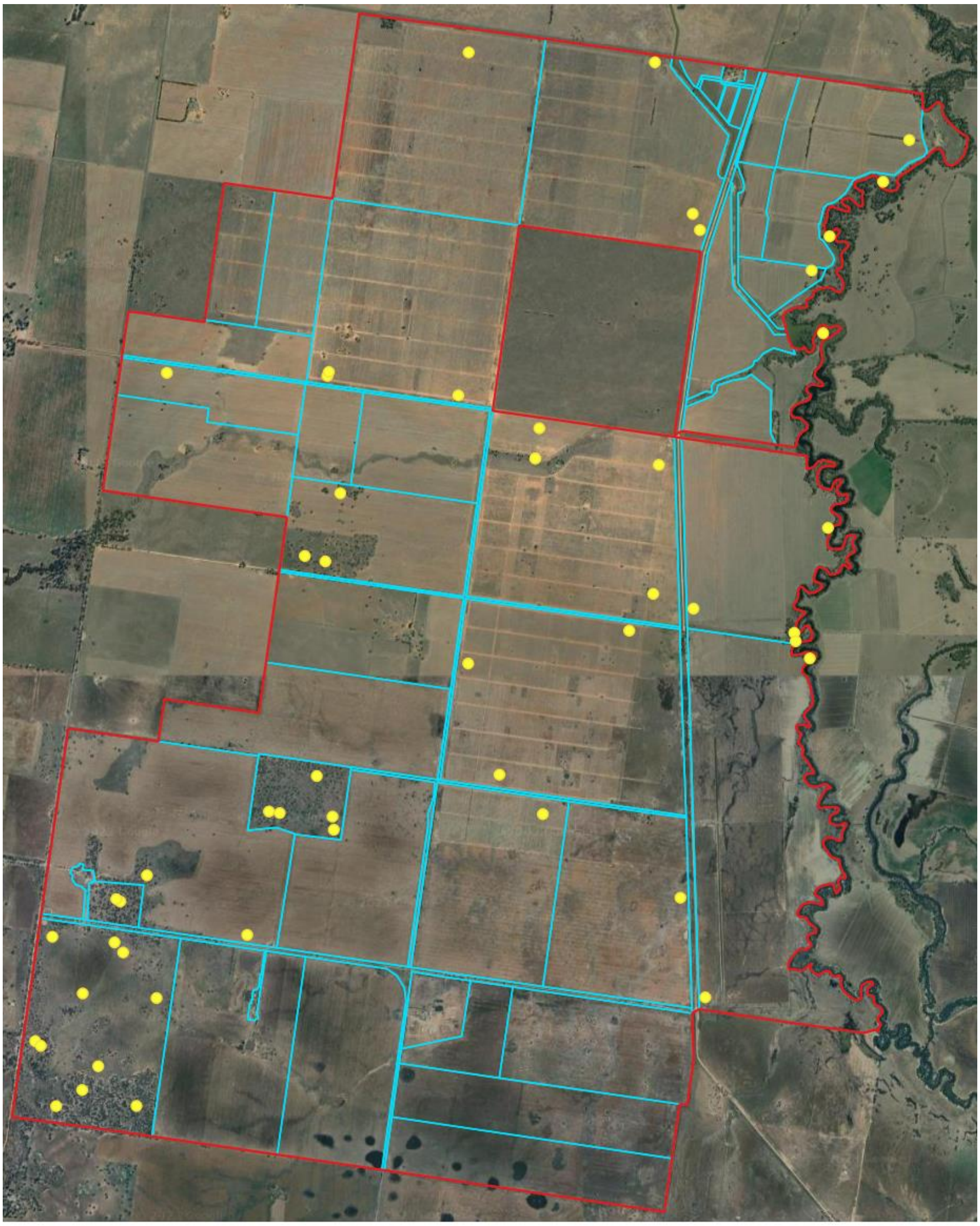

Figure B1. Location of rapid ecological assessment points (yellow dots) on example farm. Imagery: Google; Image (c) 2022 Maxar Technologies, Image (c) 2022 CNES/Airbus

A mix of measurement approaches were used to assign the final Ecosystem State (natural capital asset) to each Ecosystem Unit. These include field validation during the rapid ecological assessments by ecologists, and imputing the condition of Ecosystem Units / paddocks that were not visited and assessed in the field. Table B1 summarises this information providing details of which Ecosystem Units were assessed from direct field observations and the Ecosystem Units for which the Ecosystem State (condition) was imputed, and which Ecosystem Units were used to impute their condition.

Table B1. Example imputation log.

Ecosystem condition measurement process as @ 18/10/2021		
Condition Data Source	**Ecosystem State**	**Paddocks where the source information was used to impute the Ecosystem State**
Visited – P21	C1	P16, P21, P23, P27
Visited – P14	C2	P2
Visited – P19	C2	P15, P17, P18, P21, P22, P24, P8
Visited – P23	C2	P32, P33, P34, P35, P36, P37
Visited – P29	C2	
Visited – P9	C2	P10, P11, P17, P20, P3, P5, P6, P7
Visited – P36	C3	P38
Visited – P37	C3	P39, P40, P41, P42, P43, P44
Visited – P42	C3	
Visited – P1	DG1	P1
Visited – P12	DG1	P12
Visited – P37	DW3	River1
Visited – River2	DW3	P14, P2, P28, P9, River1
Visited – P10	EWV3	P26
Visited – P17	EWV3	
Visited – P23	EWV3	
Visited – P27	EWV3	P25
Visited – P28	EWV3	P29
Visited – P23	MG5	P28, P30, River1, River2
Visited – P39	PNT2	
Visited – P1	TW1	
Visited – P1	TW1	
Visited – P12	TW1	
Visited – P13	TW1	P1, P36
Visited – P14	TW1	P1, P12, P2
Visited – P36	TW1	P36
Visited – P37	TW3	P37, P39, River1
Visited – P21	TW4	
Visited – River1	TW4	River2
Remote Imagery	PNT2	P38, P39, P40, River2, TL1, TL2

Appendix C: Detailed methods for generating invertebrate-related ecosystem services

To account for arthropod-mediated ecosystem services, the invertebrate community was sampled for decomposers, pollinators and predators as part of the Natural Capital Accounting project. decomposers were collected from 411 sites along 83 transects across 15 farms, while pollinators and predators were collected from 636 sites from 130 transects across 36 farms in south-east Australia (see Appendix E).

Transects were located in paddocks containing canola and pastures with either (relatively) high plant species richness or low plant species richness. Transects were stratified by the vegetation type adjacent to the paddock, being either remnant vegetation (typically woodland), replanted vegetation (usually a shelterbelt) or no woody vegetation (usually a grassy roadside verge or an adjacent paddock). In all cases, samples were collected from 5 sites along each transect: in the vegetation adjacent to paddocks (-10 m), and 10 m, 30 m, 70 m and 200 m into the paddock. As such, paddocks with a minimum width of at least 400 m were used (to avoid the 200 m site being less than 200 m from the other side of the paddock).

C.1 Decomposer Community

C.1.1 Sample collection

The decomposer community was sampled on 15 farms across Victoria's wheat/sheep belt, located between Heathcote in the east and Horsham in the west. Paddocks with pastures or crops were targeted. At each site along the transect, invertebrates were sampled by scraping all litter and soil from the top 5 cm of two 15 cm X 15 cm quadrats randomly placed within a 1 m^2 quadrat at each sample point into a sealed plastic bag. In pastures, each collection was randomly located within the plot, while in the crops one sample was taken from the base of the crop itself, while the other was taken from a random position along the interrow. This resulted in two litter/soil samples per plot, each measuring 1125 cm^3 in volume. Samples contained in ziplock plastic bags were held in insulated coolers while transported to a refrigerated room (4°C) for short-term storage (a maximum of seven days from collection).

C.1.2 Extraction and sorting

In the laboratory, the contents of each sample bag was placed into a Tullgren funnel (further detail below) to extract all invertebrates from the litter and soil. Animals were stored in 70% ethanol and thereafter identified to order level and counted. This allowed for a measure of abundance to be generated (i.e. the number of animals per square metre).

Invertebrates were extracted from the collected material using Tullgren funnels, whereby an enclosed light/heat source is placed above a cylinder with a mesh grating to hold the litter/soil sample, while allowing arthropods to move through the mesh away from the light and heat source as the sample material dries. A funnel with a vial containing ethanol is placed below the mesh grating to collect and preserve the animals that fall through. Sample material was removed, rotated and replaced in the funnels after three days to facilitate effective drying. Funnels were operated for one week, or until litter and soil was dry to the touch.

Collected arthropods were visually sorted under a binocular dissecting microscope to Order level for all groups except for beetles (Coleoptera) and flies (Diptera), which were further sorted to Family level to allow for detritivore (decomposer) groups to be identified. Counts were taken, and the following size classes were assigned: small (<2 mm), medium (2-5 mm) and large (>5mm). This produced a matrix of sites versus counts of individuals of confirmed decomposer taxa. From this, we calculated the abundance of decomposers at each sampling site (n=411).

C.2 Pollinator and predator communities

C.2.1 Sample collection

Pollinator and predatory arthropods were sampled from 36 farms across Tasmania's Midlands, north-central Victoria, NSW south-west slopes and the New England Plateau. The same transect design (5 sites at varying distances from the edge of the paddock) was used as described for detritivores, across 130 transects. Pollinators and beneficial predatory invertebrates were sampled using sweep netting, whereby animals are swept from the air and vegetation with a hoop net. Samples were collected using 50 'sweeps' deployed along a 50 m transect running perpendicular to the sampling transect (or parallel to the paddock boundary). Any invertebrates captured in the nets were stored in 100% ethanol in plastic vials to transport back to the laboratory.

C.2.2 DNA extraction

From these samples, DNA was extracted and sequenced to provide high-resolution identification of taxa. This technique allows for the identification of cryptic species that may be difficult to identify visually. While DNA sequencing identifies unique species very well, the gene sequences of many taxa are not yet known. For these species, the nearest species match is provided from existing databases (usually a different species in the same genus). This allows for their ecological function to be inferred. While this methods provides high taxonomic resolution, it does not permit counts or estimates of abundance.

To use metabarcoding for arthropod identification, a non-destructive extraction technique was followed (Batovska et al. 2021). DNA was extracted from all arthropods in each sample using Illumina "QuickExtract" solution. All arthropods were contained in a 1.5 mL Eppendorf tube for extraction, but for large arthropods (e.g., honeybees, blowflies) we removed the head from the body with clean forceps to ensure the entire sample was able to fit in a single tube. The extraction process requires a 6-minute incubation at 65°C followed by a 2-minute incubation at 98°C, after which the solution containing the DNA is PCR-ready and the animals can be returned to ethanol for long-term storage. DNA concentration was standardized to 10 ng/µL before Polymerase Chain Reaction (PCR) amplification. A ~400 bp fragment of the mitochondrial Cytochrome Oxidase 1 (COI) gene was used for our metabarcoding analyses (primers BF3 and BR2 were used; Elbrecht and Leese 2017). We then ran a secondary index PCR amplification that attached a unique combination of multiplex identifier tags to each sample. Negative extraction controls were run in parallel with community samples. We cleaned each sample using AMPure magnetic beads to remove non-target size sequences and primer–dimers. PCR samples were then standardized and pooled into equimolar concentrations to produce a PCR amplicon library. The final pooled library was sequenced with 15% phiX control on the Illumina MiSeq platform using a MiSeq Reagent Kit v3.

C.3 Bioinformatics

In total, 636 samples were successfully sequenced. Sequence reads for both the forward and reverse target amplicon sequences were trimmed and filtered to remove phiX and reads that exceeded the expected nucleotide length and hence were likely to be sequence errors (Martin 2011). We merged the forward and reverse reads to create unique Amplicon Sequence Variants (ASVs) and removed chimeras. We determined species-level units by clustering ASVs at a 97% lineage similarity and conducted a BLAST search against the nucleotide database NCBI GenBank using 'MEGAN' software (Huson 2007). This produced a matrix of sites versus confirmed taxa of known functional group (eg. pollinator, predator, pest, etc). From this, we calculated the taxonomic richness of each functional group at each sampling site (n=636).

C.4 Statistical modelling

In the main accounts, we present spatially explicit models using remote sensed variables to predict ecosystem services across the entire farm. Prior to this, a 'field model' was developed for each group of interest (decomposers, pollinators and predators). This model included field data that was collected at the time of sampling, with the aim of identifying fine-scale habitat influences on arthropods. Data relating to habitat structure were collected in a 1 m^2 quadrat at each sampling site. Habitat features expected to influence abundance or species richness were measured in the field and combined with remotely-sensed variables for modelling (Table C1) using generalised additive models. This 'field model' provides information about what is influencing each group of interest at the paddock scale and helps us understand the nature of management actions that may be important to regulate arthropod services on the farm.

C.4.1 Decomposers

The most widespread and numerous invertebrate decomposers found in surveys were members of the springtail order Poduromorpha. The most common species are likely to be introduced to Australia and appear to prefer to live in disturbed ecosystems such as crops. Springtails, regardless of their origin, are likely to be having a beneficial impact on decomposition, though introduced populations of springtail may outcompete native decomposers.

At the paddock scale, several habitat features were found to show relationships with the abundance of decomposers. As decomposers live in the litter and topsoil, it follows that organic litter cover would impact their abundance (and potentially *vice versa*). Decomposer abundance decreased at litter levels above 60% cover (see Figure C1), potentially reflecting the impact of decomposers themselves on the litter (where fewer decomposers exist, litter breakdown is slower). This relationship may also reflect the preference of springtails for crops with low litter cover overall. Soil moisture also had a strong influence on the predicted decomposer abundance within the paddock: with increasing soil moisture, there is a predicted increase in decomposer abundance (see Figure C1).

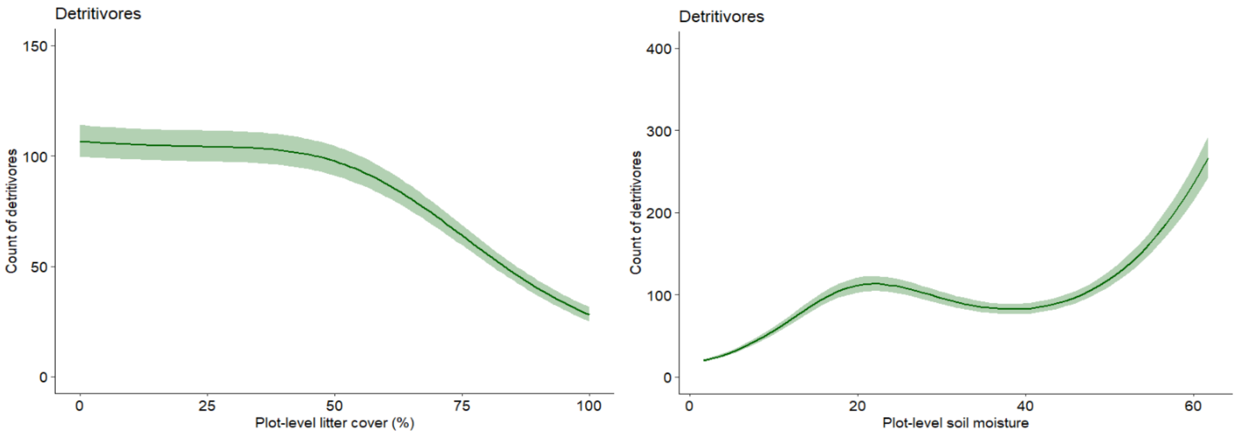

Figure C1. Predicted abundance of arthropod decomposers in the topsoil (number per 2,250 cm^3) in relation to litter cover (left) and soil moisture (right).

The field model identified an 'edge effect' in production areas, in which decomposer abundance peaked around 30 m into the paddock (see Figure C2). This relationship differed slightly depending on whether the edge of the paddock was comprised of revegetation, remnant woodland or non-woody vegetation. Decomposer abundance in production areas adjacent to remnant woodland (depicted by the green line in the graph below) showed a less pronounced peak, but a greater abundance further into the paddock than for revegetation. There was still a strong edge effect where there was no woody vegetation, suggesting that the diversity of plants in different habitats (e.g., road verges with diverse grasses and herbs) provide resources for decomposers, while having suppressive effects around the fringe of the production areas.

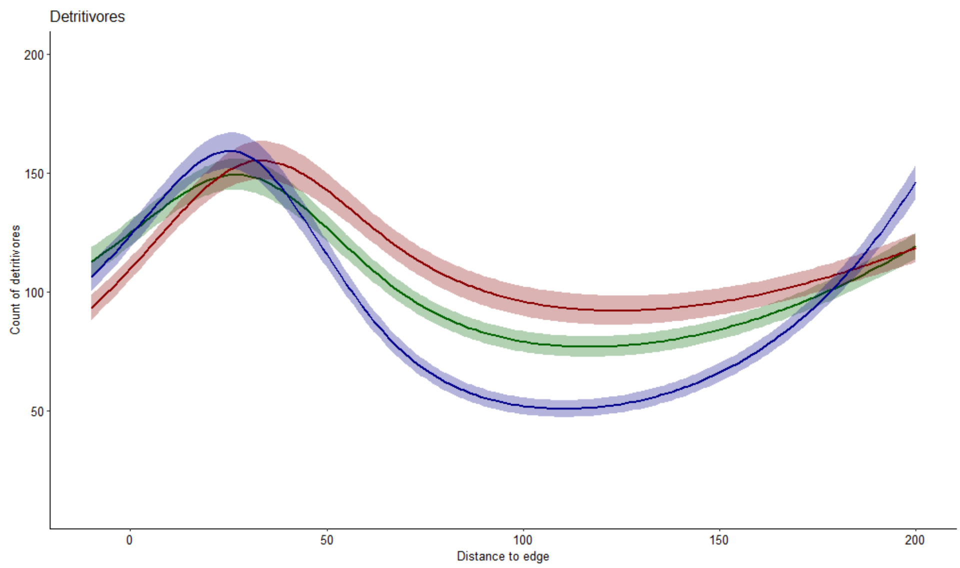

Figure C2. Predicted abundance of arthropod decomposers in the first 5 cm of topsoil (number per 2,250 cm3) in relation to distance into the paddock. The green line represents paddocks adjacent to remnant woodland; the blue line represents paddocks adjacent to revegetation; and the red line represents paddocks without adjacent woody vegetation.

C.4.2 Pollinators and predators

A similar field model (as described for decomposers above) was developed to identify the relationships between pollinator and predator species richness and ecological attributes at the paddock scale, respectively. Pollinator richness was positively associated with the edges of ecosystem types and increased with more ground cover (Figure C3).

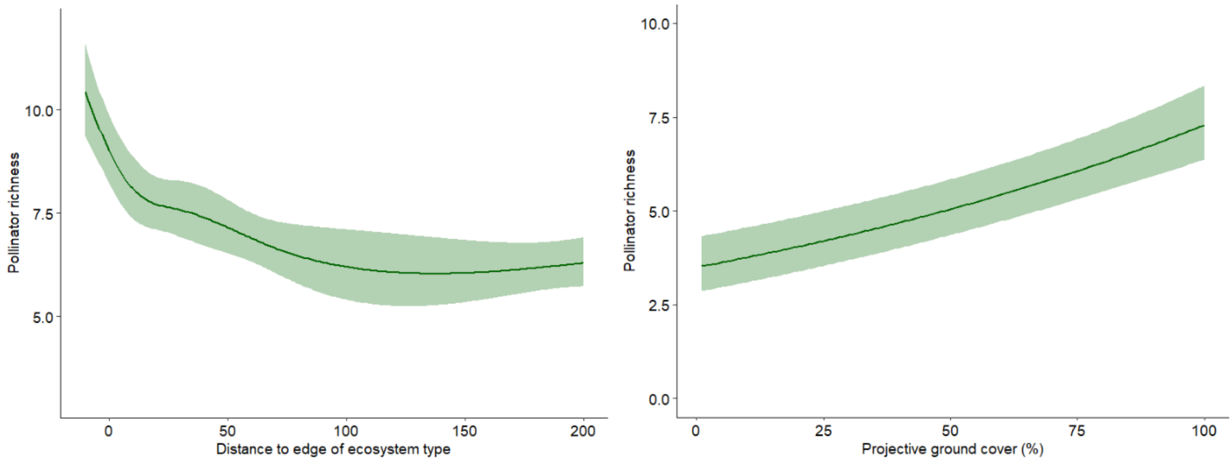

Figure C3. Pollinator richness in relation to distance from the edge of a paddock (left) and % ground cover (right).

Landscape context, including the availability of natural vegetation adjacent to crops and pastures, can influence the effectiveness of beneficials. Areas of natural vegetation can provide population reservoirs and access to additional resources for arthropods that are not available in production areas. Models of beneficial arthropod predators showed that areas closer to trees had more species (Figure C4).

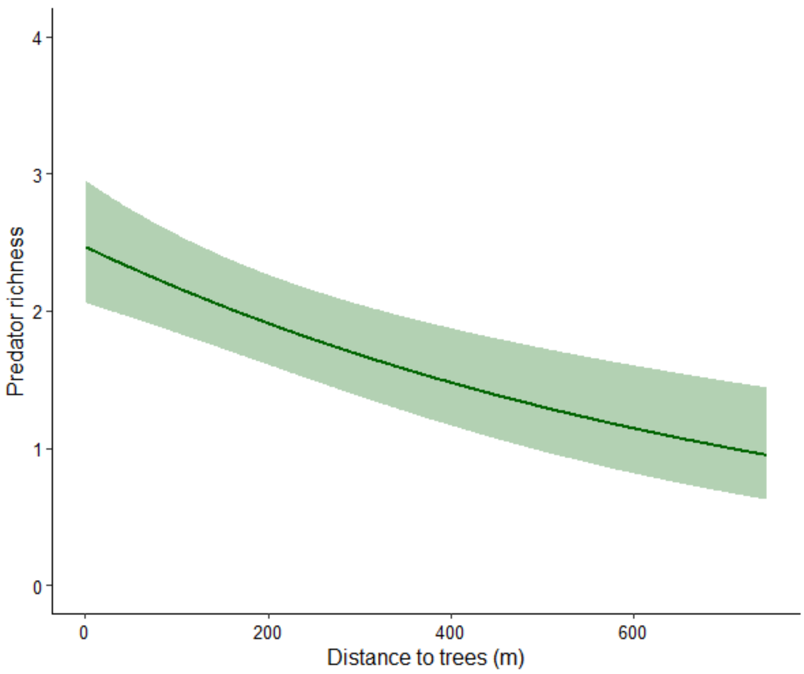

Figure C4. Richness of beneficial predatory arthropods in relation to distance from trees.

Table C1. Ecological variables included in arthropod field-based models.

Field variable	Model		
	Detritivores	**Pollinators**	**Predators**
Adjacent vegetation (remnant, revegetation or non-woody vegetation)	✓	✓	✓
Cover of bare ground	✓	✓	✓
Cover of vegetation		✓	✓
Crop type	✓	✓	
Distance from paddock edge	✓	✓	✓
Ecosystem type (state and transition model)		✓	
Litter cover	✓	✓	✓
Mean litter depth	✓		✓
Mean plant height	✓	✓	✓
Mean soil moisture	✓		
Plant species richness	✓		
Proximity to trees			✓

C.5 References

Batovska, J., Piper, A.M., Valenzuela, I., Cunningham, J.P. and Blacket, M.J. 2021. Developing a non-destructive metabarcoding protocol for detection of pest insects in bulk trap catches. Scientific Reports, 11: 7946.

Elbrecht, V. and Leese, F. 2017. Validation and development of freshwater invertebrate metabarcoding COI primers for environmental impact assessment. Frontiers in Environmental Science, 5: 1–11.

Huson, D.H., Auch, A.F., Qi, J. and Schuster, S.C. 2007. MEGAN analysis of metagenomic data. Genome Research, 17: 377–386.

Martin, M. 2011. Cutadapt removes adapter sequences from high-throughput sequencing reads. EMBnet Journal, 17: 10–12.

Appendix D: Detailed method for calculation carbon stocks and sequestration in woody vegetation

D.1 Modelling the carbon stocks

The carbon stocks stored in the woody vegetation have been modelled using FLINTpro (www.flintpro.com). The modelling is based on a spatial and temporal assessment of the woody vegetation on the farm as derived from the National Forest and Sparse Woody Vegetation Data (Version 6.0 – 2021 Release), combined with updated overlays for plantings undertaken by the property manager that may not appear in the National Forest and Sparse Woody Vegetation Data. The detailed planting information has been included to ensure that we are able to provide a more realistic picture of the carbon stocks as these plantings will often not appear in the NFSWV data for many years or may never appear if the planting is narrow (the National Forest and Sparse Woody Vegetation Data has a resolution of 30m, and currently spans from 1989 through to 2021). Other inputs to the model include ANUClimate 2.0 rainfall and temperature data (Hutchinson et al., 2021), as well as Australian Annual Fire Data[3]

For application within FLINTpro, a forest is considered to be land that contains woody vegetation which has, or has the potential to, reach more than 20% canopy cover in vegetation more than 2m in height, consistent with the definition above. The forest potential extent was defined as land that has woody vegetation (>5% canopy cover) and achieves 'forest' cover in at least three years over the simulation period (1989-2021) according to the National Forest and Sparse Woody Vegetation Data (Version 6.0 – 2021 Release). The data product used also contains the other classes detailed in the forest definition, and therefore classifies the landscape into non-woody vegetation (<5% canopy cover), sparse woody vegetation (5-19% canopy cover) and forest (>20% canopy cover). Where land does not achieve forest cover at least three points in time (between 1989 and 2021), it is treated as non-forest for the whole simulation and excluded from the assessment. The approach of treating sparse vegetation as 'forest' when it achieves forest cover was taken to reduce loss and gain events when an area fluctuates between just over and just under the 20 percent canopy threshold. This approach results in a conservative outcome of emissions and removals.

It is also important to understand that the model may underestimate the carbon stored in scattered paddock trees. Scattered paddock trees will typically not appear in the National Forest and Sparse Woody Vegetation Data and are not dense enough or large enough to be included as plantings in the overrides applied. This can be seen in Figure D1 where the green shading shows areas included in the estimation, and non-shaded areas will not be included in the carbon calculations (even where there are trees).

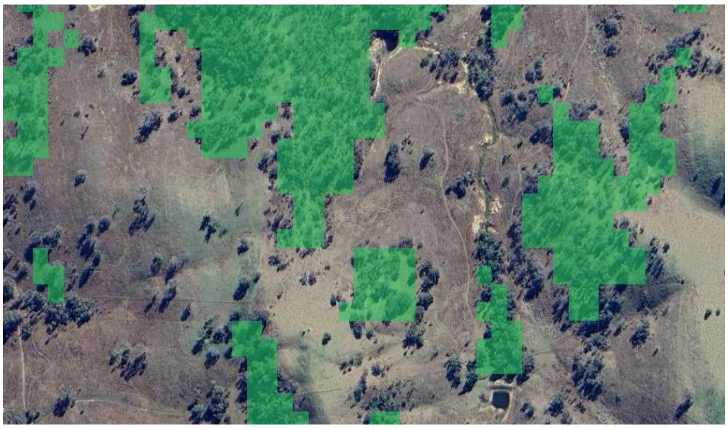

Figure D1. Example of forest and sparse woody cover (green shading)

[3] Based on an Australia wide dataset of Historical Bushfire Boundaries (https://dx.doi.org/10.26186/147763), with NAFI data used for NT. Method based on: DISER. 2021. National Inventory Report 2019

The simulation was run from 1920 through to 2050, and any pixels defined as forest in 1989 of the National Forest and Sparse Woody Vegetation Data were modelled to be planted in 1920. This provides sufficient time for the model to 'spin up' and stabilise. Forest cover changes detected in the National Forest and Sparse Woody Vegetation Data are then applied from 1989 to 2021. Data from 2022 onwards show a growth model without any clearing/loss or planned planting events. The exception to this is where a farm enterprise has plans to clear woody vegetation (thin/harvest in plantations), in which case the planned harvest events have been included in the modelled data.

The modelling may show a loss event (removal of carbon from the sink and emission to the atmosphere) for a number of reasons, including:

- Deliberate clearing events – thinning and clearing of remnant vegetation and plantations
- Fire events (controlled and wildfires) – with an immediate emission from the fire itself, along with the potential for a reduction in forest extent following the fire
- Thinning events – where the forest has thinned due to die-back, pest infestation or drought

A farm manager may not have control over all these events, although management decisions can have some influence over the severity of some of them.

It is important to understand that a loss event is not instantaneous, and that not all the carbon from a tree is considered to be emitted in the year of clearing. The model allows for some of the biomass to move into the woody debris pool, which is then emitted to the atmosphere (and also stored in soil) over a number of years following the event. This is demonstrated in Figure D2. The rate of emission from the dead organic matter pool to the atmosphere in the years following the clearing event is dependent upon local climatic factors.

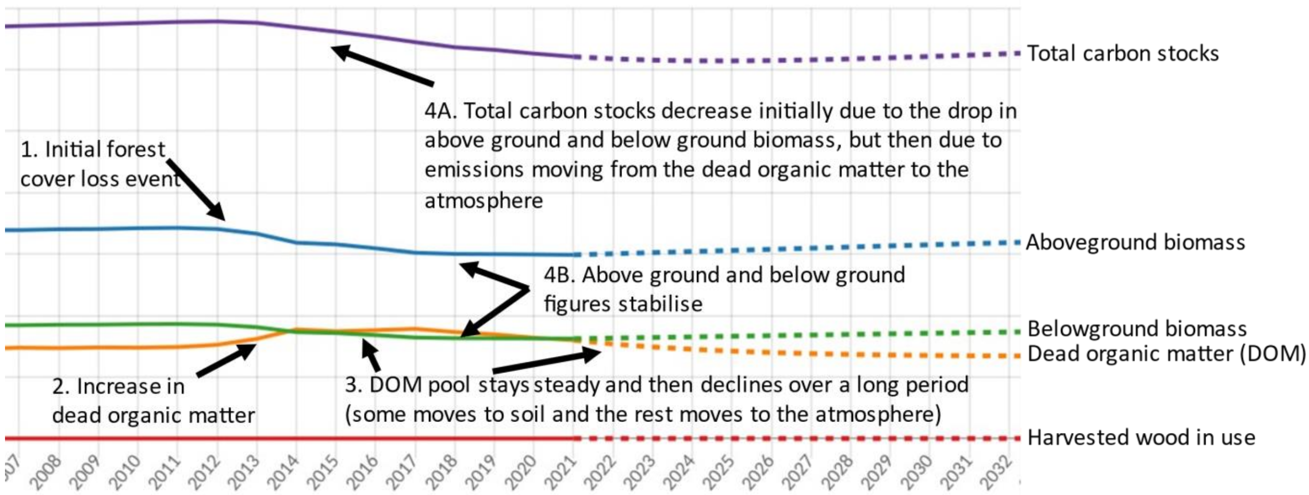

Figure D2. Carbon stock changes following a clearing event

D.2 Calculating the sequestration rate

The sequestration rate figure (used in the carbon summary and detail charts and the GHG emission summary tables in the report) is calculated using the change in total carbon stocks over the 5 years leading up to and including the latest year of production data. The time-period has been chosen to align with the timeframe of the production data used to calculate the emissions figures.

The consequence of this is that the sequestration rate figure is sensitive to the events occurring leading up to and during the 5-year window used. This can have an impact on determining whether a farm has a negative or positive carbon balance for the reporting window.

Appendix E: Farm locations and surveys conducted

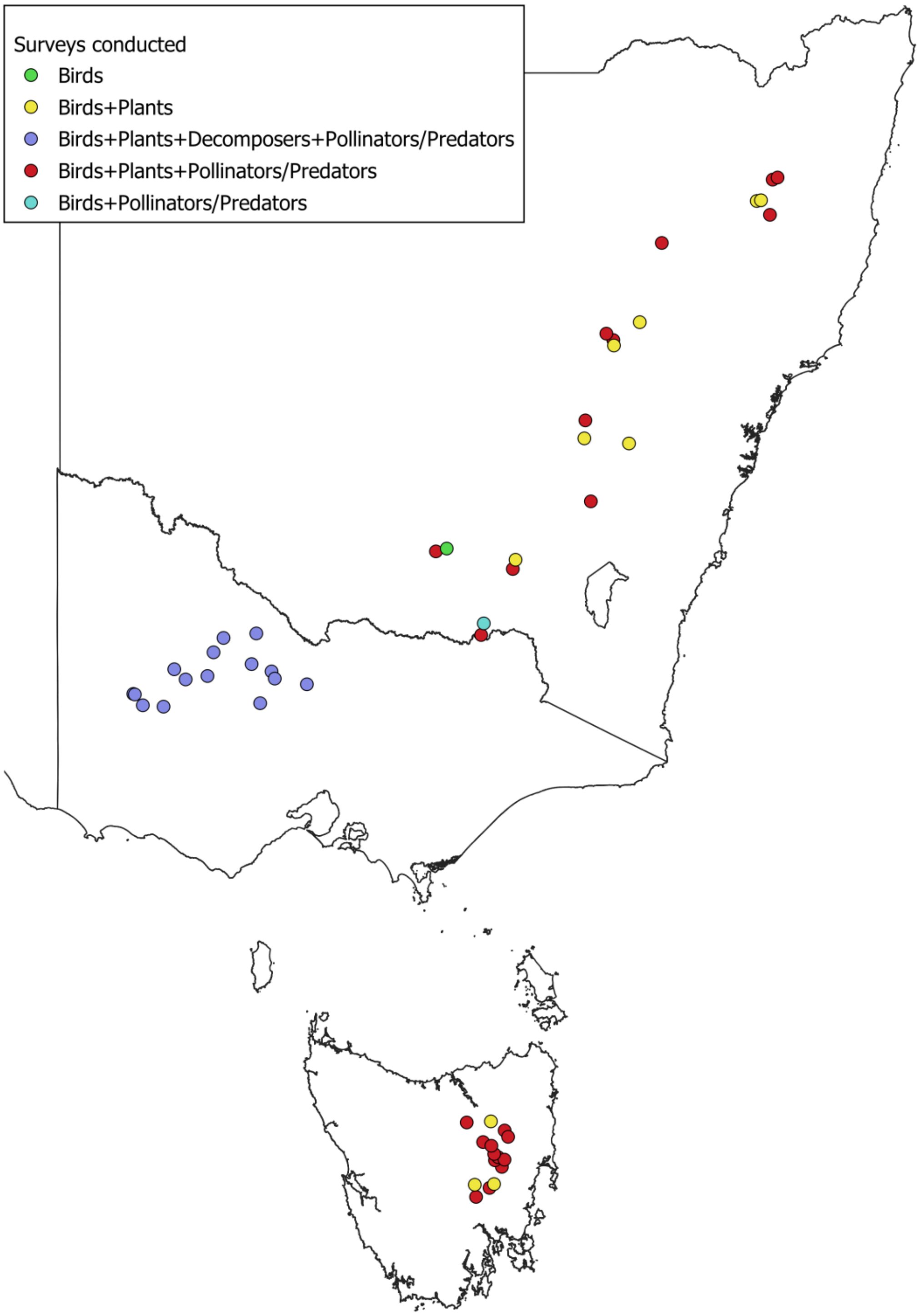

Figure E1. Location of farms across south-east Australia. Colours indicate which surveys were conducted at the farm.

Appendix F: Glossary of terms

- **Benchmark**: A standard against which the value of a particular indicator may be compared. In this account, the benchmark often represents the average value of the indicator across multiple farms based on empirical research. The benchmark is not necessarily the best or most desirable value but the average of the farms studied.
- **Biospheric source**: Of biological origin; used in the context of greenhouse gas emissions, refers to emissions from livestock and clearing and oxidation of vegetation.
- **Carbon cycle**: That part of the biogeochemical cycle by which carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere of Earth.
- **Carbon sequestration:** Is the process by which carbon dioxide (CO^2) is captured from the atmosphere and stored in natural or artificial reservoirs. It primarily occurs through photosynthesis by algae, plants and trees, and carbon is 'bound' in carbon pools in vegetation, soil or water. Technological methods like carbon capture and storage (CCS) may also remove carbon dioxide from the atmosphere. Carbon sequestration helps reduce the concentration of greenhouse gases in the atmosphere and mitigate climate change.
- **Carbon stock**: Carbon stock refers to the amount of carbon stored in a particular ecosystem or natural resource. It includes carbon stored in vegetation, soils, biomass, and other dead and living organic matter (excluding geological storages like fossil fuel reserves).
- **Condition**: In the context of natural capital, condition refers to the quality of an ecosystem state or natural resource asset. In the context of the State and Transition models used to classify ecosystem assets, condition is a measure of departure from the reference condition state.
- **Ecosystem assets**: Natural capital assets that comprised of areas of a specific ecosystem type.
- **Environmental assets**: Natural capital assets that are the individual components of the biophysical environment (e.g., minerals, water, soil).
- **Environmental performance indicators**: These are indicators used to evaluate the environmental performance of an organization or project beyond natural capital indicators. They may include measures of energy efficiency, waste management, greenhouse gas emissions, pollution levels, and other environmental factors.
- **Ecosystem state**: These refer to the categories defined in the State and Transition models, which are based on the level of departure from a pre-European, ''reference' condition (e.g., transitioning woodland 1, derived grassland 1, etc.).
- **Extent:** Extent refers to the spatial coverage or size of an ecosystem or natural resource. It measures the physical distance (for linear resources), area or volume occupied by a particular habitat, landscape, or natural feature. Evaluating the extent helps understand the distribution and availability of natural capital and assess its vulnerability to degradation or loss.
- **Fossil water**: Water contained in underground aquifers that are not able to be significantly recharged from surface water or other aquifers.
- **Geospheric source**: Of geological origin; used in the context of greenhouse gas emissions, refers to emissions from the use of fossil fuels.
- **Greenhouse gas (GHG) emissions**: Release of greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide) into the atmosphere through natural processes and human activities. Greenhouse gases absorb infrared radiation (net heat energy) emitted from the Earth's surface and trap it in the atmosphere, thus contributing to climate change.
- **Natural capital**: All biotic (living) and abiotic (non-living) natural resources that are present in a particular area that combine to generate a flow of services that are of benefit or value to people

and society. Natural capital is made up of **assets** (sometimes called **stocks**) that are physical entities that can be described in terms of their extent and condition. On a farm, natural capital includes both naturally occurring ecosystems (e.g., forests, woodlands, shrublands, grasslands and wetlands) and ecosystems that have been established and maintained by humans (e.g., pastures, crops, orchards, shelterbelts).

- **Natural capital accounting**: A method of measuring and quantifying the value of natural capital resources and assets. Natural capital accounting involves assessing the extent and condition of natural capital assets (or stocks), and the flow of ecosystem services from the natural capital stocks for a specified area (or organisation) for a particular point in time. Re-assessment enables changes in natural capital assets and ecosystem services to be accounted for.
- **Non-renewable (finite) resources**: A natural resource that cannot be readily replaced by natural processes at a pace quick enough to keep up with consumption (e.g., fossil fuels).
- **Reference state (or condition)**: The reference state represents the original or unmodified pre-industrial development condition of a particular ecosystem or natural resource. It serves as a baseline against which the current condition can be compared.
- **Riparian (zone)**: Associated with rivers, stream and wetlands; refers to the area between the waterline of a waterway and the top of the bank or the transition to upland vegetation.
- **Renewable resource**: A substance of economic value that is replenished by natural processes at a rate faster than or equal to its rate of consumption.
- **Scope 1 (GHG emissions)**: Direct greenhouse gas emissions from sources that are owned or controlled by an organization. On a farm, this includes emissions from livestock, fuels for operating vehicles, and fertilisers.
- **Scope 2 (GHG emissions)**: Indirect greenhouse gas emissions associated with the consumption of purchased electricity, heat, or steam by an organization. These emissions occur during the production of the energy consumed by the organization.
- **Scope 3 (GHG emissions)**: Indirect greenhouse gas emissions that occur throughout an organization's value chain, including both upstream and downstream activities. On a farm, this includes emissions generated by off-farm suppliers in producing and transporting inputs such as sheep and cattle purchases, synthetic fertiliser, superphosphate, urea, and feed (grain, hay/silage, lucerne). Also included are off-farm emissions from electricity use (e.g., transmission losses) and upstream fuel consumption (e.g., extraction of fossil fuels).
- **State and Transition Model (STM)**: Conceptual models of ecosystem dynamics that represent alternative condition states for a particular ecosystem and the processes or disturbances that trigger and drive changes (transitions) between states. State-and-transition models can be used to summarize relationships between land management and disturbances and the ecological state (or condition) of a site.