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EDITED BY
Helda Morales,
The South Border College (ECOSUR), Mexico

REVIEWED BY
Stewart Diemont,
SUNY College of Environmental Science and Forestry, United States
Nathan Einbinder,
University of Plymouth, United Kingdom

*CORRESPONDENCE
Adam D. Canning
adam.canning@jcu.edu.au

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Rediscovering wild food to diversify production across Australia's agricultural landscapes

Adam D. Canning *

Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville, QLD, Australia

Conventional agriculture currently relies on the intensive and expansive growth of a small number of monocultures, this is both risky for food security and is causing substantial environmental degradation. Crops are typically grown far from their native origins, enduring climates, pests, and diseases that they have little evolutionary adaptation to. As a result, farming practices involve modifying the environment to suit the crop, often *via* practices including vegetation clearing, drainage, irrigation, tilling, and the application of fertilizers, pesticides, and herbicides. One avenue for improvement, however, is the diversification of monoculture agricultural systems with traditional foods native to the area. Native foods benefit from evolutionary history, enabling adaptation to local environmental conditions, reducing the need for environmental modifications and external inputs. Traditional use of native foods in Australia has a rich history, yet the commercial production of native foods remains small compared with conventional crops, such as wheat, barley and sugarcane. Identifying what native crops can grow where would be a first step in scoping potential native food industries and supporting farmers seeking to diversify their cropping. In this study, I modeled the potentially suitable distributions of 177 native food and forage species across Australia, given their climate and soil preferences. The coastal areas of Queensland's wet tropics, south-east Queensland, New South Wales, and Victoria were predicted to support the greatest diversity of native food and forage species (as high 80–120 species). These areas also correspond to the nation's most agriculturally intensive areas, including much of the Murray-Darling Basin, suggesting high potential for the diversification of existing intensive monocultures. Native crops with the most expansive potential distribution include Acacia trees, Maloga bean, bush plum, Emu apple, native millet, and bush tomatoes, with these crops largely being tolerant of vast areas of semi-arid conditions. In addition to greater food security, if diverse native cropping results in greater ecosystem service provisioning, through carbon storage, reduced water usage, reduced nutrient runoff, or greater habitat provision, then payment for ecosystem service schemes could also provide supplemental farm income.

KEYWORDS

traditional foods, ecosystem service, regenerative agriculture, polyculture agriculture, bush tucker, native food plants

Introduction

With the global population expected to reach nine billion inhabitants by 2050, global food demand is expected to increase by 35–56% by 2050 from 2010 levels (van Dijk et al., 2021). While it is estimated that current food production can meet this demand, challenges exist in ensuring food is adequately distributed to all populations, exacerbated by the climate change driven displacement of people and crops (Schmidhuber and Tubiello, 2007; Wheeler and von Braun, 2013). Achieving global food security is a monumental challenge, dependent on the availability of a diversity of quality foods that are accessible, usable, and stable (Mc Carthy et al., 2018; Kaseva et al., 2019; Barrett, 2021). In addition to removing food trade barriers (Wood et al., 2018; Kinnunen et al., 2020), developing agronomic knowledge on locally-suitable crops can help improve local food sovereignty and buffer against shocks in traded food (Altieri et al., 2012; Leventon and Laudan, 2017; Gliessman et al., 2019). Yet to date, improving food security has been largely reliant on the growth of a low diversity of monocultures. Despite over 50,000 potentially edible plant species globally, only an approximate 300 species are commercially cultivated (Jacques and Jacques, 2012; Massawe et al., 2016), with 90% of global caloric intake is fueled by just 30 crops (Hammer et al., 2003). The global reliance on a low diversity of monocultures puts food security ambitions at risk, particularly with a changing climate (Khoury et al., 2014), and is driving widespread decline in environmental conditions (Altieri, 2009; Stoate et al., 2009; Ramankutty et al., 2018).

With the global food system largely reliant on a small number of crops grown in vast monocultures, many crops are consequently grown well-beyond their natural range and ecosystems (Meyer et al., 2012; Milla et al., 2020). To accommodate this range expansion, landscapes have been heavily modified *via* the clearing of native vegetation, drainage, irrigation, and application of agrochemicals such as fertilisers, pesticides and herbicides (Altieri, 2009; Stoate et al., 2009; Ramankutty et al., 2018). Native ecosystems within these modified landscapes are often lost completely or disturbed (Dudley and Alexander, 2017). Aquatic systems, for example, face altered hydrology as vegetation coverage and drainage affects rainfall runoff patterns, eutrophication from the losses of fertilizer and livestock excretion, and sedimentation from eroding soils that have reduced vegetative protection (Tilman et al., 2001, 2002a; Awuchi et al., 2020; Gaugler et al., 2020). Terrestrial ecosystems and their species have also been lost or disturbed as the vegetative base of the food web is removed or altered (Tylianakis et al., 2008; Powers and Jetz, 2019). The low diversity of monoculture food systems puts global food security at risk as they have little resilience to climate disruptions (Khoury et al., 2014), pests and diseases (Grab et al., 2018; Ekroth et al., 2019), and nutrient limitations—all reinforcing the need for alteration of farming environments (Altieri, 2009; Crews et al., 2018). While engineering innovations may improve the efficiency of water and agrochemical applications (King, 2017; Shafi et al., 2019), they can be unreliable, resource and energy intensive, vulnerable to outages and extreme weather events, and are often cost-prohibitive to adopt (Tzounis et al., 2017; Shafi et al., 2019). In the USA and Canada, despite heavy investment in improving yields from fertilizer inputs, Hamilton et al. (2013) found no improvement in edible energy efficiency over the past two decades. Put simply, engineering will not alone solve the global issues brought about by mass monoculture. Jevon's Paradox presents an issue for engineering advances, which states that, in the long term, an increase in resource use efficiency will result in increased resource consumption rather than a decrease (Giampietro and Mayumi, 2018). Engineering advances may even exacerbate the ecological impacts of agriculture if farmers use the advances to expand industrial models of agriculture beyond the boundaries of their land's natural capacity (Woodhouse, 2010; Ceddia et al., 2013; Hamilton et al., 2013; Sears et al., 2018; Hamant, 2020).

Creating a sustainable food system will inevitably require the application of ecology to agricultural/food systems or "agroecology" (Gliessman, 2016; Wezel et al., 2020; Bezner Kerr et al., 2021). Rather than having agricultural practices combat natural environments, they will need to work with natural environments and grow a diversity of crops that thrive in those environments (Kremen et al., 2012; Massawe et al., 2016; Crews et al., 2018), as was largely practiced by many indigenous cultures for thousands of years (Singh and Singh, 2017; Suárez-Torres et al., 2017; Figueroa-Helland et al., 2018). Crop diversity can help increase resilience to external stressors, such as extreme weather events and pest and diseases, improve nutrient and water cycling, and help meet nutritional needs through provision a greater richness of phytochemicals (Provenza et al., 2015; Ijaz et al., 2019). Furthermore, using a diversity of crops can help increase the resilience of small-scale landholders (Aguilar-Støen et al., 2009; Meldrum et al., 2018; Ticktin et al., 2018).

In addition to having a diversity of crops, agricultural practices that promote, rather than degrade, the health of agroecosystems would need to be adopted, such as traditional practices that enabled sustained indigenous food production for thousands of years (Critchley et al., 1994; Altieri, 2004; Brookfield and Padoch, 2010), and those promoted through regenerative agriculture (Tilman et al., 2002b; LaCanne and Lundgren, 2018; Lal, 2020; Newton et al., 2020). While traditional agricultural practices are highly varied, some similarities in traditional agroecosystems often exist including: high species diversity; high structural diversity (temporally and spatially); efficient nutrient recycling; complex ecological networks; positive energy efficiency ratios with little to no fossil fuel input; and use of local plants and animals (Altieri, 2004;

TABLE 1 Agricultural strategies commonly used in regenerating agroecosystems (LaCanne and Lundgren, 2018).

Strategies	Rationale
No or low tillage	Reducing tillage helps to maintain and improve soil health and allowing mycorrhizal fungi to develop extensively (Kabir, 2011; dos Santos Soares et al., 2019). This typically results in increased soil carbon, improved nutrient use efficiency and runoff (Sun et al., 2015), and reduced weeds, pests and diseases (Shelef et al., 2017; Norris and Congreves, 2018).
Cover crops	Cover crops are those planted during the fallow periods of normal crop production with an objective of enhancing multiple ecosystem services. In addition to protecting bare soil from erosion and compaction, the increased plant residues can help increase soil carbon, improve soil structure, help control pests and weeds, reduce methane and nitrous oxide emissions, and maximise water and nutrient use efficiencies. They can also provide habitat or sustenance for biodiversity, including pollinators (Kaye and Quemada, 2017; Osipitan et al., 2018; Adetunji et al., 2020; Chapagain et al., 2020; Ogilvie et al., 2021).
Adaptive Multi-Paddock Grazing	Adaptive Multi-paddock (AMP) grazing seeks to use short periods of intensive grazing of livestock on small land patches, followed by long rest periods, to maximise plant growth rate. The system is not scheduled or prescribed but involves constant observation of pastures (to avoid over and under grazing) and livestock moved accordingly. AMP grazing has been shown to increase primary and secondary productivity, improve the spread of manures, restore preferred herbaceous species, and increase soil organic carbon, soil fertility, water-holding capacity, and economic profitability (Teague, 2018; Teague and Kreuter, 2020).
Crop diversity	Having a diversity of crops interacting within an agroecosystem, rather than a monoculture, has been shown to increase the water and nutrient use efficiency, improve support for biodiversity, increase the diversity of soil microbial assemblages, and reduce soil erosion and soil-borne diseases (Yang et al., 2020).
Incorporation of perennials and trees, including agroforestry	Incorporating trees can benefit the regeneration of agroecosystems *via* providing increased shading that can reduce of evaporation of soil moisture, increased groundcover that increases water infiltration and reducing surface runoff, the extensive root systems improve soil porosity, increase soil organic matter, and improve nutrient use efficiency by intercepting leached nutrients (Dollinger and Jose, 2018; Zhu et al., 2019).
Restoration of natural habitats	Restoring natural habitats, such as forest patches, wetlands, riparian buffer zones and wildlife corridors, can support the delivery of numerous ecosystem services. Potential services include flood control, improved water quality, habitat for wildlife, pest and weed control, recreation opportunity, carbon sequestration, and habitat for game animals (Mace et al., 2012; Cole et al., 2020; Canning et al., 2021).
Use organic rather than inorganic fertilisers, including composts, mulch, green manure and other crop residues	Organic fertilisers involve the redistribution of nutrient-rich organic matter (both plant and animal based), rather than synthetically produced fertilisers typically in a mineral and plant-available form. Not only do organic fertilisers reduce the demand for fossil fuels, but they also improve soil structure and have been shown to strongly increase the abundance and diversity of nematodes Puissant et al., 2021. Animal manure has been shown to reduce soil bulk density and increase the infiltration and holding capacity of water (Rayne and Aula, 2020). While biofertilisers are microbial inoculations to soil that help to make existing nutrients available for plant uptake (Daniel et al., 2022).
Ecologically-based pest, weed and disease management	As opposed to using synthetic chemicals to control unwanted species, ecologically-based approaches are highly varied, but some common principles include: Ensure niches are occupied to prevent invaders capitalising on available resources; using Island Biogeography Theory to inform management of source populations; using biological control agents; companion cropping with species that deter unwanted species and attract desirable species (Brzozowski and Mazourek, 2018; Baker et al., 2020; Egan et al., 2020; MacLaren et al., 2020).

Gliessman, 2015). Within regenerative agriculture, the aim is to adopt practices that can help regenerate, rather than degrade, the health of agroecosystems and their connected ecosystems, and often include no or low tillage, crop diversity, ecologically-based pest and weed control, restoration of natural habitats, the incorporation of permanent vegetation (such as trees), adaptive multi-paddock grazing and using organic fertilisers (Table 1).

Diversification could occur by the incorporation of native plants, benefiting from evolution to local environmental conditions (Shelef et al., 2017; Singh and Singh, 2017; Ijaz et al., 2019). Being accustomed to the local environment, native plants have potential for use in no or low tillage strategies, which can maintain and improve soil health (Kabir, 2011; dos Santos Soares et al., 2019), consequently increase soil carbon, improving nutrient use efficiency, reduce runoff (Sun et al., 2015), and reducing weeds, pests and diseases (Shelef et al., 2017).

In Australia, the impacts of farming global staple crops are no different from the rest of the globe. Aquatic ecosystems, such as the Great Barrier Reef (a World Heritage Area) and the Murray-Darling River (the nation's largest freshwater ecosystem), are suffering from the resulting nutrient enrichment, hydrological change, and sedimentation (Pittock et al., 2011; Davis et al., 2016; Brodie et al., 2017). Australia does, however, have a rich history and diverse array of traditional foods or "bush tucker" arising from native plants that hold potential for diversifying agricultural landscapes with locally resilient species (Sultanbawa and Sultanbawa, 2016). For instance, many Australian native plants have evolved to survive and thrive with low phosphorus availability, with sclerophylly, hairy roots and associations with mycorrhizal fungi being common. Some native plants even respond negatively to the addition of phosphorus (Handreck, 1997). Beyond the environmental benefits, there are also potential human, social, cultural, and economic benefits. With respect to human health, an initial screening of 13 native foods found a high diversity of phytochemicals, and the majority having greater availability of minerals than blueberries (a well-recognized health food) (Konczak et al., 2009; Sommano et al., 2013; Richmond et al., 2019). Socially and culturally, the native foods sector also provides an opportunity for Indigenous Australians to use their traditional knowledge systems, including long-developed social and environmental management practices, to create new livelihoods and enterprises (Buchanan, 2014; Laurie, 2020; Jarvis et al., 2022).

Realizing Australia's native food potential, however, requires substantial knowledge gaps to be filled to inform financial decisions. Key gaps include understanding what species can grow where, growth and production rates, efficacy of propagation techniques, market and value-adding opportunities, industry structure and size, industry risks and limitations, potential Indigenous business models, and methods to best mobilise knowledge (Clarke, 2012; Jarvis et al., 2022).

In this study, I seek to inform the gap of what species can grow where, by using modelling to identify land parcels with soil and climate characteristics likely to support the growth of an array of bush tucker plants. This would enable farmers to identify what native crops could be supported within the natural capacity of their farming system, and help agricultural industries scope the production potential of different native crops.

Methods

Species data

A compilation of 177 terrestrial native plant species, excluding grasses, with known use potential for producing human foods or livestock forage was compiled from the literature (Dear et al., 2008; Konczak et al., 2009; Revell et al., 2013; Sultanbawa and Sultanbawa, 2016; Isaacs, 2019; Richmond et al., 2019). For all species identified (Supplementary Table S1), all observations (including location) from across Australia were extracted from the Atlas of Living Australia (ALA), yielding 647,180 records. ALA is a large database that collates sightings of animals from a wide range of organisations and contributors (Belbin and Williams, 2016). Given the likely differences in survey method and intensity among observers (Canning and Waltham, 2021), which could reduce the reliability of abundance data, this analysis only examined the presence of a species, rather than the abundance. Furthermore, surveys could not be used to indicate species absence. Nonetheless, the ALA dataset represents the most comprehensive observation dataset over the entire spatial extent and is, therefore, the best data available for this analysis.

Environmental variables

At all observation locations, statistics for 19 climate variables were extracted from the WorldClim2 database (Fick and Hijmans, 2017), and 12 soil variables from the Soil and Landscape Grid of Australia (SLGA; Table 1; Grundy et al., 2015; Viscarra Rossel et al., 2015).

WorldClim 2 provides 19 climate metrics for baseline conditions (Table 2), using long-term average between 1970 and 2000, from between 9,000 and 60,000 weather stations, that were then interpolated to provide global coverage at 1 km^2 resolutions (Fick and Hijmans, 2017). Globally, the cross-validated correlations on baseline data were 0.86 for precipitation, 0.76 for wind speed, and $\geq$ 0.99 for temperature and humidity, though there is regional variation between models and parameters (Fick and Hijmans, 2017).

The SLGA provides Australia-wide coverage of 11 continuous soil attributes at 0.008 km^2 (90 x 90 m) resolutions (Table 2), across regolith depths between 0 and 2 m (Grundy et al., 2015; Viscarra Rossel et al., 2015), with predictions conforming to the GlobalSoilMap specifications (Arrouays et al., 2014). For this study, only those for regolith depths between 30 and 60 cm were extracted. The SLGA three-dimensional soil maps were derived from spatial models informed by 281,202 soil profiles in the national soil visible–near infrared database (NSVNIRD) and 1,315 sites from the national soil visible–near infrared database (Viscarra Rossel et al., 2015). Across all attributes mapped, models between 30 and 70% of their total variation, with near-surface estimates typically having greater accuracy with more training data (Viscarra Rossel et al., 2015).

Random forest models

Random forests are a machine learning method that uses a collection of regression trees, whereby each tree is fitted to a bootstrapped sample (with replacement) and then validated on the out-of-bag sample (Breiman, 2001). Random forest predictions are the average of the predictions of each tree. Regression trees, and consequently random forests, work by partitioning observations at splits of predictors that minimise the sum of squares error. They have a high level of flexibility, can handle non-linear relationships and complex interactions, and do not require cross-validation or a separate testing dataset

TABLE 2 The climatic variables (Fick and Hijmans, 2017) and the soil variables (Grundy et al., 2015) used in random forest modelling to predict the potential distributions of bush foods across Australia.

Variable group	Variable code	Description
Climate variables	PrecColdQ (mm)	Precipitation of Coldest Quarter
	PrecWarmQ (mm)	Precipitation of Warmest Quarter
	PrecDryQ (mm)	Precipitation of Driest Quarter
	PrecWetQ (mm)	Precipitation of Wettest Quarter
	PrecCOV	Precipitation Seasonality (Coefficient of Variation)
	PrecDryMonth (mm)	Precipitation of Driest Month
	PrecWetMonth (mm)	Precipitation of Wettest Month
	AnnPrec (mm)	Annual Precipitation
	MTempColdQ (°C)	Mean Temperature of Coldest Quarter
	MTempWarmQ (°C)	Mean Temperature of Warmest Quarter
	MTempDryQ (°C)	Mean Temperature of Driest Quarter
	MTempWetQ (°C)	Mean Temperature of Wettest Quarter
	TempRange (°C)	Temperature Annual Range (MaxTWarmMonth-MinTColdMonth)
	MinTColdMonth (°C)	Min Temperature of Coldest Month
	MaxTWarmMonth (°C)	Max Temperature of Warmest Month
	TempSD	Temperature Seasonality (standard deviation ×100)
	Isothermality	Isothermality (MeanDiurnTRange/TempRange) (×100)
	MeanDiurnTRange	Mean Diurnal Range (Mean of monthly (max temp - min temp))
	AnnMeanTemp (°C)	Annual Mean Temperature
Soil variables	Bulk Density (g/cm^3)	Bulk Density of the whole soil (including coarse fragments) in mass per unit volume by a method equivalent to the core method
	Organic Carbon (%)	Mass fraction of carbon by weight in the < 2 mm soil material as determined by dry combustion at 900 Celcius
	Clay (%)	<2 um mass fraction of the <2 mm soil material determined using the pipette method
	Silt (%)	2–20 um mass fraction of the <2 mm soil material determined using the pipette method
	Sand (%)	20 um–2 mm mass fraction of the <2 mm soil material determined using the pipette method
	pH (CaCl2)	pH of 1:5 soil/0.01M calcium chloride extract
	Available Water Capacity (%)	Available water capacity computed for each of the specified depth increments
	Total Nitrogen (%)	Mass fraction of total nitrogen in the soil by weight
	Total Phosphorus (%)	Mass fraction of total phosphorus in the soil by weight
	Effective Cation Exchange Capacity (meq/100g)	Cations extracted using barium chloride (BaCl2) plus exchangeable H + Al
	Depth of Regolith (m)	Depth to hard rock. Depth is inclusive of all regolith.
	Depth of Soil (m)	Depth of soil profile (A & B horizons)

as each tree is constructed using a different bootstrap sample (Cutler et al., 2007; Hastie et al., 2009; Ellis et al., 2012).

Random Forests were used to model the probability of occurrence for all species (Supplementary Table S1) based on all the climatic and soil characteristics (Table 2), relative to a random background, using the "randomForest" function (trees=500) from the randomForest package in R (Liaw and Wiener, 2002; R Core Team, 2016). As the occurrence data used was presence-only, and could not indicate absence, an equal number of random background locations were used instead of absences, to achieve a balanced presence-background predictive model. Model performance was assessed by calculating the area under the receiver operating curve (AUC-ROC), calculated using the 'auc' function from the pROC package (Robin et al., 2011). According to Šimundić (2009), AUC-ROC between 0.7 and 0.8 indicate good diagnostic accuracy, while 0.8–0.9 indicates very good, and 0.9–1.0 indicates excellent accuracy. The "importance" function, from the randomForest package (Liaw and Wiener, 2002), then used to identify the globally important variables, which measure the decrease in Gini index from splitting on each variable, averaged over all trees.

Predicting species suitability across australia

Using the random forest models, the suitability of each species (where AUC-ROC >0.7) was predicted across the entirety of Australia using the soil and climate data extracted from the centroids of 18,827 polygons. Polygons were derived by intersect the 419 bio-subregion polygons, as mapped by the Interim Biogeographic Regionalisation for Australia (Thackway and Cresswell, 1995; Cummings and Hardy, 2000; IBRA, 2020), and soil order polygons according to the Australian Soil Classification (McKenzie et al., 2012). The IBRA (V7.0) classifies Australia's landscape into 89 bioregions and 419 subregions, based on climate, geology, landform, and native species presence (Thackway and Cresswell, 1995; Cummings and Hardy, 2000), and is endorsed by all levels of government for use under *Australia's Strategy for the National Reserve System 2009–2030*. IBRA is a landscape-scale classification, and the intersection with soil order provides a greater resolution.

Results

Of the initial 177 species identified, 150 species (225 taxonomic groups including subspecies and varieties) had sufficient observations, model accuracy and suitability predicted across Australia (Supplementary Table S2). In general, across all species models, the maximum temperature of the warmest month and quarter, precipitation of the driest month and quarter, and precipitation of the coldest quarter, were the most important climatic and soil variables, though substantial differences in variable importance were observed between species (Supplementary Table S2).

Across the nation, the diversity of potentially suitable native crops ranged from 0 to 120 for a given parcel (Figure 1). Areas with the climate and soil characteristics with potential for supporting the highest diversity of native crops include the coastal areas of New South Wales, Victoria and northern Tasmania, and in Queensland's Wet Tropics (Figure 1). While the central and mid-south areas of Western Australia had the lowest potential diversity of native crops.

The native crops with the most expansive potential distribution include Acacia trees (*Acacia* spp.), Maloga bean (*Vigna lanceolata*), bush plum (*Carissa spinarum*), Emu apple (*Owenia acidula*), native millet (*Panicum decompositum*), and bush tomatoes (*Solanum* spp; Supplementary Table S2).

Of the six native crops most commonly used and in demand (Robbins, 2008), Lemon Myrtle (*Backhousia citriodora*) is predicted to be suitable along the east coast (Figure 1A), Native Citrus (*Citrus* spp.) across south-east Queensland and central New South Wales (Figure 1B), Davidson Plum (*Davidsonia* spp.) across northern coastal Queensland, coastal New South Wales and Tasmania (Figure 1C), Quandong (*Santalum acuminatum*) across southern areas of west Western Australia, South Australia and Victoria (Figure 1D), Bush Tomato (*Solanum centrale*) across central Western Australia and Northern Territory (Figure 1E), and Native Pepper (*Tasmannia lanceolata*) across southern New South Wales and Tasmania (Figure 1F).

Given the need to urgently reduce nutrient and sediment losses from the sugarcane-growing regions of the Great Barrier Reef catchment, I also compiled a list a species predicted to be widely suitable across the intensive sugarcane-growing areas of the Burdekin region (dry tropical climate) and the Ingham (wet tropical climate) regions (Table 3). For each species, I have indicated the type of edible produced, approximate forest strata position, approximate growth rate, and whether it is a legume, to help inform agroforestry, including syntropics, and farm planning. Within the Ingham region there were 32 widely suitable terrestrial bush foods, while there were 18 across the lower Burdekin region (Table 3).

Discussion

Modelling of bush foods

Diversifying agricultural landscapes with native foods provides an avenue to improve the resilience and ecological values of contemporary agricultural systems dominated by monocultures. Here I modelled the potential suitability of land parcels across Australia to support 177 native crops, with the majority of species (150) having good to excellent diagnostic accuracy. The probability of suitability for most species was primarily influenced the maximum temperatures and rainfall. While it is not surprising that these climatic variables are influential in predicting diversity, it may also be possible that other factors are driving the patterns, such as energetic and landscape characteristics, which appear visually correlative (Venevsky and Veneskaia, 2003), and evolutionary histories (Martin, 2006; Cowling et al., 2015). Nonetheless, the present study focused on identifying potentially suitable land parcels for native crops, not the drivers of diversity, and the high performance of the models permits land identification. While the land parcels presented here are large-scale, the models can also be used to predict at higher resolutions, such as the farm-scale. It is also likely that this study has not encapsulated all potential native foods, with traditional knowledge systems likely to inform gaps. Furthermore, most work scoping native shrubs for livestock forage has focused on southern Australia, with northern Australia requiring substantially more work (Dear et al., 2008; Monjardino et al., 2010; Revell et al., 2013). As knowledge on additional species, and new observations arise, the modelling framework applied here should be updated in time to include additional the information. Further work should also be undertaken to scope the use of native plants for fibres, and the use of native aquatic plants.

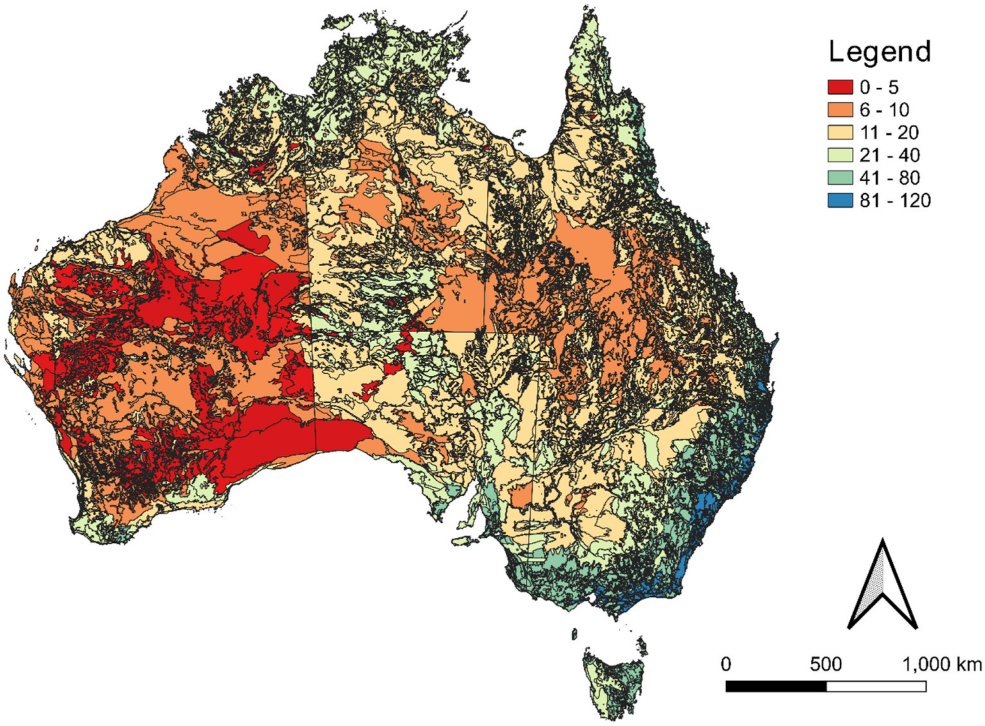

FIGURE 1
The potential number of native plant food and forage species predicted to be suitable across Australia, with locations delineated by soil order mapping and IBRA mapping (McKenzie et al., 2012; IBRA, 2020).

National-scale diversity patterns

Essentially all the major agricultural regions that currently support intensive monoculture systems were suitable for supporting between 20 and 120 species, with the coastal areas of Queensland's wet tropics, south-east Queensland, New South Wales, and Victoria having the most versatile land parcels. While the inland desert areas of Western Australia were predicted to have the least potential diversity.

Those with the most expansive potential distributions are also drought resilient species, such as Acacias, native millet, and bush tomatoes, and are found across areas of central Australia. With the two most expansive groups, Acacia and Maloga bean, also both being legumes and can support nitrogen fixation. While much of central Australia is arid or semi-arid, vegetation present in these areas can be traced back to when central Australia was humid and supported rainforest, with the few species remaining being those that could tolerate or adapt to dry climates and infertile soils (Martin, 2006). As 70% of Australia is arid or semi-arid with soils of poor fertility, species that can survive in dry climates and mitigate nutrient deficiencies, have a much greater potential range than those dependent on regular rainfall and fertile soils (Stafford Smith and Morton, 1990).

Murray-darling basin

The Murray-Darling Basin has experienced substantial hydrological alterations to support cropping and survival through dry periods (Leblanc et al., 2012), with large water demands causing not only declines in freshwater ecological health, but major social and cultural impacts, including the loss of livelihoods for indigenous communities, as well as public resources lost to buying back water for environmental flows (Davies et al., 2010; Connell and Grafton, 2011). Within the Murray-Darling basin, there was a high diversity of potential native crops predicted, meaning there is also large opportunity for native crop integration to be a strong measure towards improving the Basin's freshwater ecosystems, which has been given little consideration to date (Pittock et al., 2011). Vegetation native to the Basin have been shown to be highly resilient to prolonged extreme drought (Capon and Reid, 2016). Consequently, a landscape dominated by a diversity of crops native to the basin are unlikely to demand the same

TABLE 3 Bush food species predicted to be widely suitable across the sugarcane-growing areas of the Burdekin (dry tropical climate) and Ingham (wet tropical climate) regions of the Great Barrier Reef catchment, along with the type of edible produce, approximate forest strata position, indicative growth rate, and whether the species is a legume.

Scientific name	Common name	Burdekin	Ingham	Produce	Strata	Growth rate	Legume
Acacia holosericea	Soapbush Wattle	Yes	Yes	Seeds	Pioneer emergent	Fast	Yes
Acacia victoriae subsp. *fasciaria*	Bramble Wattle	Yes	Yes	Seeds	Pioneer emergent	Fast	Yes
Acronychia acidula	Lemon Aspen	No	Yes	Fruit	High	Slow	No
Alpinia caerulea	Native Ginger	No	Yes	Herb	Low	Fast	No
Antidesma bunius	Bignay Currant	No	Yes	Fruit	Medium	Slow	No
Archirhodomyrtus beckleri	Rose Myrtle	No	Yes	Fruit	Medium	Slow	No
Athertonia diversifolia	Atherton Oak	No	Yes	Fruit	High	Slow	No
Backhousia citriodora	Lemon Myrtle	No	Yes	Flowers, fruit & leaves	High	Slow	No
Buchanania arborescens	Sparrow's Mango	No	Yes	Fruit	High	Slow	No
Carissa spinarum	Conkerberry	Yes	No	Fruit	Medium	Fast	No
Davidsonia pruriens	Davidson's Plum	No	Yes	Fruit	Medium	Slow	No
Dioscorea bulbifera	Aerial Yam	Yes	Yes	Bulbil	Low	Fast	Yes
Enchylaena tomentosa var. *glabra*	Ruby Saltbush	No	Yes	Fruit	Medium	Fast	No
Ficus racemosa	Cluster Fig	Yes	Yes	Fruit	Emergent	Slow	No
Melaleuca leucadendra	Weeping Paperbark	Yes	Yes	Essential oil	Emergent	Fast	No
Melaleuca viridiflora	Broad-leaved Paperbark	Yes	Yes	Essential oil	Emergent	Fast	No
Melastoma affine	Blue Tongue	No	Yes	Fruit	Low	Fast	No
Melodorum leichhardtii	Zig-zag Vine	Yes	Yes	Fruit	Medium	Fast	No
Mimusops elengi	Spanish Cherry	Yes	Yes	Fruit	Medium	Slow	No
Morinda citrifolia	Noni	No	Yes	Fruit	Medium	Fast	No
Ocimum tenuiflorum	Holy Basil	Yes	Yes	Herb	Low	Fast	No
Owenia acidula	Emu Apple	Yes	No	Fruit	Medium	Slow	No
Pandanus tectorius	Screw Pine	Yes	Yes	Fruit	Medium	Slow	No
Panicum decompositum var. *decompositum*	Australian Millet	Yes	No	Seeds	Low	Fast	No
Panicum decompositum var. *tenuius*	Australian Millet	Yes	Yes	Seeds	Low	Fast	No
Physalis minima	Native Gooseberry	No	Yes	Fruit	Low	Fast	No
Pleiogynium timoriense	Burdekin Plum	Yes	No	Fruit	Emergent	Slow	No
Podocarpus elatus	Illawarra Plum	No	Yes	Fruit	High	Slow	No
Rubus moluccanus	Broad-leaf Bramble	No	Yes	Fruit	Medium	Fast	No
Rubus probus	Atherton Raspberry	No	Yes	Fruit	Medium	Fast	No
Semecarpus australiensis	Native Cashew	No	Yes	Fruit	Emergent	Slow	No
Solanum ellipticum	Bush Tomato	Yes	No	Fruit	Low	Fast	No
Sterculia quadrifida	Peanut Tree	Yes	Yes	Seeds	High	Slow	No
Syzygium australe	Brush Cherry	No	Yes	Fruit	High	Slow	No
Syzygium fibrosum	Small Red Bush Apple	No	Yes	Fruit	Medium	Slow	No
Syzygium luehmannii	Riberry	No	Yes	Fruit	Medium	Slow	No
Vigna lanceolata	Maloga Bean/Bush carrot	Yes	Yes	Tuberous root & Bean	Low	Fast	Yes

volume of water as existing crops (Miers, 2004; Ryder et al., 2008; Sultanbawa and Sultanbawa, 2016), allowing more natural hydrological regimes to improve river health (Pittock et al., 2011).

Furthermore, five of the six native foods identified by Robbins (2008) that are already commercially grown, with developed agronomy, in demand and with growth potential, are also suitable within the Basin. These include Lemon Myrtle, Native Citrus, Davidson Plum, Quandong (a tart-tasting, dry textured fruit), and Native Pepper (Figure 2). However, focussing solely on these five crops may lead to non-native monocultures simply being replaced by native monocultures that are devoid of the benefits of multi-species crops and do little to improve the environmental woes of the present agricultural system. Instead, these crops should be grown in combination with other native crops suitable within the same land parcel, which will require further investigations into the design of native agroforestry regimes.

Great Barrier Reef region

In the Great Barrier Reef region, the Queensland Government has a target to reduce dissolved inorganic nitrogen (DIN) and sediment losses to the reef by 60% and 25% respectively by 2025 to protect reef health (*Reef 2050 Water Quality Improvement Plan*). Despite only occupying 1.3% of the catchment area, DIN from sugarcane fertiliser losses accounts for 42% of the DIN exported to the reef (McCloskey et al., 2021). Transitioning to multi-species, multi-story agroforestry growing bush foods could be one option for reducing these losses. As an example, in Table 3 I showcase the bush foods predicted to be widely suitable across the intensive sugarcane growing areas of the Ingham (wet tropics) and Burdekin (dry tropics) regions, for which 32 and 18 species were identified, respectively. I also emphasise the word transition, as for many a large-scale transition from sugarcane to a multi-species native food cropping system, that at present has little industry and market, would be unfeasible. The transition could begin with small-scale trials where native foods are incorporated within existing sugarcane systems, either intercropped or grown during the rotation's fallow. A suitable intercrop would be low growing to prevent shading sugarcane, fast growing to recover from sugarcane harvesting damage every 12–18 months, and easily harvested in a way that does not damage sugarcane. Options to explore could include aerial yam, blue tongue, holy basil, and Australian millet. During the fallow period, maloga bean/bush carrot could be grown as a leguminous cash crop. Not only would a maloga bean rotation fix nitrogen for the next sugarcane crop, thereby reducing fertiliser demands, but it could potentially also reduce the pressure of lesion nematodes. Recent trials within the region found that leguminous rotation crops significantly reduced Lesion nematodes (*Pratylenchus zeae*) relative to continuous sugarcane cropping (Haplin et al., 2020). If, however, a new agroecological system was to be developed with agroforestry, rather than an intercropped-sugarcane system, then a greater diversity of species could be incorporated as species across all strata and growth rates could be included.

The need to identify suitable crop combinations

In developing successful agroforestry regimes, it will be necessary to further investigate the within-forest ecological requirements (e.g., light, and mutualistic relationships), growth rates and nutrient demands. To further assist with planning suitable regimes, growth models could be incorporated into an easy-to-use modelling platform, similar to the Agroforestry Design Tool in the USA (Elevitch and Logan, 2021). Understanding the strategies each species uses to survive in their local environment and potential multi-species crop assemblages will also be necessary for successful cultivation. As the plants are derived from natural ecosystems, it is likely that many will be co-dependent on other species. For example, Quandongs are hemi-parasitic, relying on a host plant, for water and nutrients. In the natural environment, they tend to rely on nitrogen fixing trees, such as *Acacia* and *Casuarina*, and usually have multiple hosts simultaneously (Australian National Botanic Gardens and Centre for Australian National Biodiversity Research, 2012). Failure to identify dependencies and suitable grafting techniques could result in a failure to thrive in a farmed environment. However, by growing Quandongs with *Acacia*, then not only can native foods be sourced from both species, but the nitrogen-fixation by mycorrhizal bacteria in *Acacia* can help minimize dependence on fertilizers. This is an example of just one simple multi-species synergy, with many more potential combinations possible. Combinations will need to be specific to the location and objectives as not all species are suitable at all locations. Attempts to grow crops out of their suitable habitat will likely result in crop failure and reliance on environmental alterations and external inputs (Ryder et al., 2008; Sultanbawa and Sultanbawa, 2016). While this is no small task, traditional knowledge by indigenous who have a long history of cultivating native foods can provide a foundation to build from Bliege Bird et al. (2008), Gerritsen (2010), Paterson (2018).

Indigenous business opportunities

Indigenous traditional knowledge also provides an opportunity for the development of culturally appropriate and Indigenous-led business and supply chain models within the emerging bush foods sector (Jarvis et al., 2022). Traditional

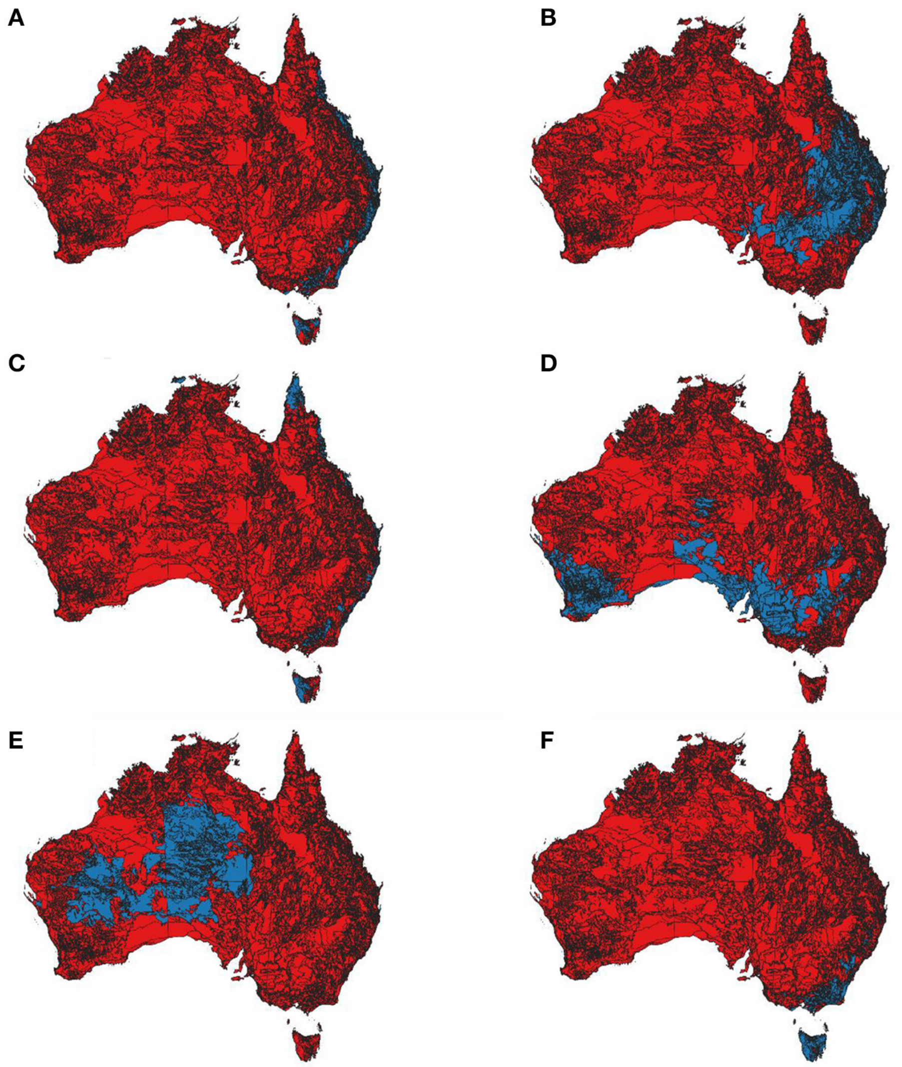

FIGURE 2
Predicted suitability of the six native crops most used and in demand (Robbins, 2008). These include **(A)** Lemon Myrtle (*Backhousia citriodora*); **(B)** Native Citrus (*Citrus* spp.); **(C)** Davidson Plum (*Davidsonia* spp.); **(D)** Quandong (*Santalum acuminatum*); **(E)** Bush Tomato (*Solanum centrale*), and **(F)** Native Pepper (*Tasmannia lanceolata*). Blue indicated the suitable environmental range, while red indicates the unsuitable range, with locations delineated by soil order mapping and IBRA mapping (McKenzie et al., 2012; IBRA, 2020).

knowledge often constitutes substantial Indigenous cultural and intellectual property (ICIP), developed and passed on from generation to generation. While the use of Indigenous knowledge is vital for sector development, the protection, use and accessibility of ICIP needs to be balanced with benefits derived from using the ICIP commercially. Managing ICIP challenges may be done within existing intellectual property legislation but will also need to consider the place-based nature of ICIP (Jarvis et al., 2022). IP Australia, an Australian Government entity, seek to protect the Indigenous Knowledge of Aboriginal and Torres Strait Islanders (IP Australia, 2021), and suggest four actions that need advancing: (1) Establishing an Indigenous Advisory Panel to provide a formalised Indigenous voice to IP Australia; (2) Enhance the trademarks and designs systems to prevent rights being granted over IK in circumstances that Aboriginal or Torres Strait Islander people or communities consider is inappropriate, unfair or offensive; (3) Introduce new requirements to declare the source of Indigenous Knowledge used in new innovations; and (4) Introduce labelling schemes that distinguish authentic Aboriginal or Torres Strait Islander goods (IP Australia, 2021). Researchers should also aim to ensure that partnering with Indigenous does not simply result in the extraction of Indigenous Knowledge but is collaborative, and that all partners co-design, co-conduct, co-govern, and co-author research projects (Maclean et al., 2021).

Ecosystem service markets for supplemental income

One of the largest barriers for new entrants into Australia's native foods market is the lack of developed industries and heightened financial risk. One way to potentially hedge bets and reduce risk would be by also diversifying income streams. Given that diverse agroforestry regimes can also deliver substantial ecosystem services (the benefits nature provides to humans) when compared with conventional agriculture (Idol et al., 2011; Torralba et al., 2016; Kay et al., 2019), then native agroforestry farms could also consider designs that have the potential to attract payments for providing ecosystem services (PES) (Farley and Costanza, 2010; Rodríguez-Ortega et al., 2018; Salzman et al., 2018; Canning et al., 2021). Across Australia, the most prevalent PES is the Carbon Emissions Reduction Fund, which makes payments to farmers for the generation of carbon credits (representing the storage or reduction of carbon). Credits are derived from the adoption of new agronomic practices and systems, including increasing soil carbon, aboveground vegetation, and reducing livestock emissions, beyond that expected from baseline farming conditions. For example, a case study in Northern Territory, demonstrated that in the top 1m of soil, grassland sites stored approximately 25 t C/ha, while sites with trees remaining (tropical open forest savannah) stored between 30 and 70 t C/ha (Chen et al., 2005; Australian Government Chief Scientist, 2009). Excluding the aboveground carbon storage, the difference of 5-45 t C/ha, at an approximate carbon trading price of $19 AUD/t C (June 2021 quarter, based on Australian Carbon Credit Unit trading), corresponds to an additional value between $95-855 AUD 2021 at the open savannah sites than the grassland sites (Australian Government Clean Energy Regulator, 2021). This represents a substantial increase in value, particularly when applied across large cattle stations (>1,000–10,000 ha). In the Great Barrier Reef catchment, schemes are emerging that fund farmers for adopting practices that reduce nutrient runoff or provide habitat for Cassowaries (*Casuarius* spp.) (Eco-Markets Australia, 2020; Terrain Natural Resource Management, 2020). In the Murray-Darling Basin, markets exist to fund farmers for the better management of water and supporting flow regulation (Wheeler et al., 2014; Settre et al., 2019). While PES opportunities are increasing, maximising participation will require easy access, low administration and assessment burden, clear assessment methodologies, strong guidance on permanence requirements, and the ability to bundle payments from multiple services (Farley and Costanza, 2010; Rodríguez-Ortega et al., 2018; Salzman et al., 2018; Canning et al., 2021). Payments for ecosystem services not only helps to diversify income and improve financial stability, but they help support farming systems that advance, rather than erode, progress towards critical environmental aspirations.

Conclusion

Conventional agriculture in Australia, like many parts of the world, is dominated by extensive monocultures is a key driver of biodiversity loss, climate change, alteration of hydrological cycles, and the sedimentation and eutrophication of aquatic ecosystems. Here I used models of environmental suitability for 177 native bush foods to scope the potential for a diverse bush foods sectors underpinned by diverse native agroforestry. Fortunately, the regions potentially supporting the greatest richness of bush food species are also those currently most at-stress from intensive monocultured agriculture, such as the Murray-Darling basin and the Great Barrier Reef catchment, meaning there is ample scope in those regions to transform the agricultural landscapes with a diversity of native foods using regenerative practices. This form of agriculture has the potential to support new Indigenous-led business models and attract supplemental income from the provision of ecosystem services. Although further work is required to better understand crop combinations, cultivation methods and to develop markets, a stark change in current agriculture is needed, and the potential benefits for humanity and the ecosystems we are part of are vast.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

AC conceived the idea, carried out the analysis, and wrote the manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.865580/full#supplementary-material

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