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Final report

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1 Dedication and Acknowledgments

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2 Executive summary

Fiji's climate is conducive to agriculture, although locally-grown food crops presently account for only about 40% of the population's food energy requirements. Much of the nation's land area is steep, with the 16 % that is suitable for mechanised agriculture increasingly diverted to other uses, including tourism, residential and other urban developments. Nevertheless, researchers have consistently observed that Fiji's agricultural potential is largely underutilised. In particular, there is long-standing strong policy recognition in Fiji of the need to improve management of the large areas of seasonally dry sloping lands in northern and western parts of Viti Levu and Vanua Levu. Horticultural crops are, in general, not commercially viable on these low-quality sites that are subjected to wildfires and cyclones. However, these lands do represent a substantial low-opportunity cost land base upon which silvopastoral systems (livestock and trees on the same land management unit) could be expanded in Fiji.

As evidenced in many parts of the world where silvopastoral systems are practiced, grazing by livestock can keep fuel loads low to reduce wildfire frequency and severity, and landholders can benefit from a diversified income stream from livestock and timber. Although cyclones present a risk to trees, the existence in Fiji of tens of thousands of hectares of pine (*Pinus caribaea* var. *hondurensis*) and mahogany (*Swietenia* macrophylla) plantations, which are typically managed over 20 to 40-year rotations, respectively, suggests timber crops can be grown. However, appropriate site-species matching and silviculture will be critically important. There is strong alignment of potential expansion of silvopastoral systems with Fiji's contemporary development priorities, including: (a) improving human health, food security, and rural employment; (b) poverty alleviation; (c) reducing trade deficits in agricultural and wood products; and (d) encouraging sustainable resource management through sequestering carbon, as well as reducing soil erosion, flooding, landslide and wildfire risk.

Fijian policy makers lack information on the overall economic cost-benefit impact of improved management of seasonally dry sloping land. This research represents a preliminary investigation of barriers, opportunities, costs and benefits to help address this knowledge gap. There were four main research objectives.

1. To examine the barriers and constraints to sloping land agroforestry in Fiji, and identify gender-inclusive policy and institutional frameworks and instruments to overcome these and facilitate the establishment of silvopastoral systems.
2. To identify potentially suitable combinations of pasture, livestock and tree species for silvopastoral systems on seasonally dry, sloping land areas on Viti Levu and Vanua Levu. Given large variation in previously published estimates of sloping land with agroforestry potential, this objective included a geospatial analysis to improve land availability estimates.
3. To collate production, cost and revenue data for individual tree and livestock species, and evaluate the financial performance (from a landholder perspective) of selected silvopastoral systems for alternative business models.
4. To develop and evaluate a regional-scale silvopastoral system adoption scenario.

A desktop review of Fiji's policies, strategies and other public governance documents, as well published and grey literature, was undertaken to examine the policy settings, barriers and constraints to sloping land agroforestry in Fiji, and identify possible policy and institutional frameworks and instruments to overcome these. The analysis indicated that there are strong policy aspirations for agroforestry, and institutional settings through which these could be progressed, but human and capital resources are not currently directed towards them. Significant and well-funded processes and programs are in play to which agroforestry is well suited as a solution and which (if targeted) could galvanise resources. Examples include climate change resilience, food security and One Health.

A preliminary geospatial analysis performed in Arc GIS with data from Google Earth, the NASA Fire Information for Resource Management (FIRM) system, and the Shuttle Radar Topography Mission (SRTM), revealed 229,000 ha of seasonally dry sloping lands on Viti Levu that are likely to have low opportunity cost, but are potentially suited to establishment of silvopastoral systems. This is in addition to and greater in area than the land area presently classified as agricultural in Fiji.

A broad literature review was undertaken of tree species which have been recommended for forestry and agroforestry in Fiji. One-on-one interviews were conducted with Fijian and Australian experts with knowledge of tree growing, forestry and agroforestry. Of the 98 native and exotic tree species identified in the literature, 13 species were identified by at least 2 experts as capable of achieving a reasonable growth rate within the biophysical and climatic constraints of Fiji's seasonally dry sloping lands. The top-five tree species were selected for silvopastoral system scenario development and evaluation, while *Leucaena leucocephala* was also selected for inclusion due to its suitability as a host for sandalwood, and to provide an improved tropical pasture scenario. On the basis of recommendations from experts, a total of nine grazing systems for cattle were developed for analysis:

1. Vesi (*Intsia bijuga*) (planted into a 'light-well' provided by a pine nurse crop);
2. Teak (*Tectona grandis*);
3. Pine (*Pinus caribaea* var. *hondurensis*);
4. Spotted gum (*Corymbia citriodora* subsp. *citriodora*);
5. Sandalwood (generic sandalwood, *Santalum spp.*) with stylo (intermediate host, *Stylosanthes spp.*) and leucaena (long-term host, *Leucaena leucocephala*);
6. Tropical pasture only (no timber production);
7. Leucaena improved tropical pasture (no timber production);
8. Spotted gum with leucaena improved tropical pasture; and
9. Spotted gum timber plantation (no cattle production).

Systems 1 to 5, and 8 are silvopastoral systems that generate income from cattle and timber. Systems 6 and 7 are grazing systems that generate income from cattle only. System 9 is a plantation forestry system that generates income from timber only. Where possible, published species growth models were employed; however, growth models were developed for Fiji from scarce data for vesi and spotted gum. A mathematical programming model was developed to optimise cattle herd structure over the lifetime of the investment as pasture production declined under the maturing trees. This model was integrated with a discounted cash flow analysis that evaluated the financial performance of each system on a per hectare basis.

All modelled systems generated a positive land expectation value (LEV) at an 8 % real (net of inflation) discount rate. The LEV of sandalwood silvopastoral systems were an order of magnitude higher than the other systems evaluated. However, cautious interpretation is warranted, because there are uncertainties about sandalwood growth rates and the market prices for plantation sandalwood in the study area. Also, relative to the other systems modelled, sandalwood investment costs and labour requirements are much higher, and sandalwood is the least resilient species to wildfire throughout the rotation.

The financial performance of leucaena improved tropical pasture exceeded all non-sandalwood silvopastoral systems, except the spotted gum with leucaena system. Given the propensity for leucaena to become an environmental weed, caution may need to be exercised about adoption of leucaena systems until a sterile form is available.

For non-sandalwood silvopastoral systems, 100 ha was found to be about the minimum farm size necessary such that all management costs could be covered by annual produce revenues, including an adequate farm household income. Spotted gum was found to be the best-performing non-sandalwood silvopastoral system, with pine a close second. Spotted gum and pine are also the two most resilient species to wildfire among those evaluated. Teak and vesi silvopastoral systems were relatively poor performers, with vesi being the only silvopastoral system to generate lower returns than the tropical pasture only scenario (no timber production).

There are large economic benefits potentially associated with silvopastoral system expansion in Fiji. If only 30,000 ha (13 %) of the seasonally dry, sloping lands on Viti Levu were developed as spotted gum silvopastoral systems, this could:

- increase national formal beef production by 25 %;
- increase long-term annual log production by 33 %;
- increase annual regional farmgate incomes by F$26 million, plus larger derived income benefits throughout the livestock and forestry industry value chains;
- increase direct regional employment in cattle production and forestry by about 368 formal full-time equivalent jobs, and also increase employment indirectly ‘upstream’ and ‘downstream’ throughout the livestock and wood products value chains; and
- increase on-site carbon sequestration by 1.13 million tonnes (4.16 million tonnes of CO_2e).

Limitations of the research performed included:

- limited consultation with relevant policy-makers, implementers and local people about the existing policies, plans for their development and implementation, and linkages with the broader suite of land related programs in Fiji. This was due to changes in the project design and travel restrictions due to COVID-19;
- a lack of ground-truthing opportunities associated with the spatial analyses undertaken;
- a dearth of financial, and tree, pasture and livestock growth data relevant for silvopastoral systems in seasonally dry sloping areas of Fiji; and
- that the financial and economic analyses have not explicitly accounted for wildfire and cyclone risk, as well as costs associated with providing permanent watering points on farm for livestock where this may be needed.

The research highlighted the need for long-term species trials, which is strongly supported by Fijian government ministries, the timber industry and experts on Fijian livestock and forestry industries. In time, these trials could greatly improve the precision of financial performance estimates, support decisions about which species to grow, and inform ‘fine-tuning’ of management regimes.

Future refinements of the mathematical model and financial analyses could be made by working closely with Fijian partners to: (a) convert the models from deterministic to stochastic; (b) incorporate geospatial data to accommodate spatial heterogeneity in production potential; (c) accommodate wildfire and cyclone risk; (d) extend the models to account for other benefits, such as carbon sequestration; and (e) update growth models and financial data, including methods and costs for providing permanent watering points for livestock where this is needed.

Ultimately, recommended silvopastoral systems would need testing with targeted local communities to understand their willingness to adopt and maintain them, to identify any socio-cultural barriers, including to participation by marginalised groups, including women. Compatibility with policy settings and programs, and acceptability to policy-makers, ministries and other stakeholders also needs to be more thoroughly assessed.

3 Background

In Fiji, the agricultural net per capita production index declined by 38 % from 122 in 1990 to 76 in 2016 (Palanivel and Shah, 2021). Over the last few decades, rapid urbanisation, coupled with declining interest in agriculture, including agroforestry, has had adverse effects on livelihoods (human health, food security, rural employment opportunities and poverty) and the Fiji economy. Locally-grown food crops presently only account for about 40% of the Fijian population's food energy requirements (FAO, 2003; National Food and Nutrition Centre, 2007; Commonwealth of Australia, 2011; Roberts *et al.*, 2011; Shah *et al.*, 2018; Palanivel and Shah, 2021). Furthermore, Fijian diets have trended away from traditional root crops, green leafy vegetables and fresh fish, towards imported foods, especially highly processed packaged foods, fatty foods, flour-based food products, rice and sugar. These dietary changes have brought with them substantial public health and productivity costs, including increasingly prevalent non-communicable diseases such as increased hypertension and cardiovascular disease, type 2 diabetes, obesity and associated micronutrient deficiencies (FAO, 2003; Commonwealth of Australia, 2011; Shah *et al.*, 2018).

Fiji consists of about 330 islands, though about 87% of the total land area of 1.827 million ha is contained in the two islands of Viti Levu and Vanua Levu. While Fiji's climate is conducive to agriculture, much of the nation's land area is steep, and presents challenges for farming. Only about 16% (about 300,000 ha) of the land is suitable, and used, for mechanised agriculture, and much of this land is being diverted for other purposes, including residential development, tourism and other urban investments (Tabaiwalu, 2010; Simmons, 2016). Indeed, between 1997 and 2015, arable land as a share of land area in Fiji decreased on average by 0.45% per year (Knoema.com 2018). Nevertheless, many researchers have observed that Fiji's agricultural potential for food production is largely underutilised, with hundreds of thousands of hectares that are potentially suitable for agroforestry, including silvopastoral systems, not being efficiently utilised (Foraete, 2002; Bolawaqatabu, 2004; Roberts *et al.*, 2011; Datt, 2016).

In particular, there are large areas of sloping lands in the 'rain shadow' northern and western parts of Viti Levu and Vanua Levu, which are now dominated by low quality grasses (notably *Pennisetum polystachio*), shrubs, vines and tree species including the invasive weed, African tulip (*Spathodea campanulata*) (Figure 1). There is long-standing recognition in Fiji of the need to improve management of these seasonally dry sloping lands, and agroforestry has frequently been recommended as a major part of the solution (Leslie and Ratukalou, 2002; Ministry of Agriculture, 2007; Bacolod *et al.*, 2014; Fiji REDD+ Secretariat, 2016; Harrison and Karim, 2016). Horticultural crops are, in general, not commercially viable on these low-quality sites subjected to cyclones and wildfires. However, these areas do represent a substantial low-opportunity-cost land base upon which to expand silvopastoral systems in Fiji.

Silvopastoral systems involve the deliberate growing of trees, animals and the pastures they consume on the same land management unit. Silvopastoral systems are typically less labour-intensive than cropping and other forms of agroforestry, which may be considered an advantage. In Australia, large areas of lower quality agricultural land, including sloping land in fire-prone landscapes, are managed as silvopastoral systems with cattle. Figure 2 is illustrative of a native forest spotted gum (*Corymbia citriodora* ssp. *variegata*) silvopastoral system on low-quality sloping land in southern Queensland. Grazing by livestock keeps fuels low, which reduces wildfire risk (i.e. $\textit{probability of wildfire}_i$ x ($\textit{ecological}_i$ + $\textit{economic}_i$ *damage costs*), for wildfire intensity i), and the landholder can benefit from a diversified income stream from timber and cattle. Cyclones present an additional risk to silvopastoral systems in Fiji; however, the existence of tens of thousands of hectares of *Pinus caribaea* var. *hondurensis* and *Swietenia macrophylla* plantations managed over long rotations for timber production in Fiji, suggests timber crops can be grown.

Figure 1 Seasonally dry sloping land in northern Viti Levu

Source: Project team photo, 2018.

Figure 2 A spotted gum native forest silvopastoral system on low site quality sloping land in southern Queensland.

Source: Francis *et al.* (2022).

Agriculture and forestry are important contributors to the Fijian economy (see Appendix A). For example, in 2019, agriculture (crop and livestock) and forestry (including wood product manufacture) accounted for F$1.3 billion (11 %) and F$0.16 billion (1.4 %) of Fiji's gross domestic product (GDP), respectively (Fiji Ministry of Agriculture, 2021; Fiji Ministry of Forestry, 2021a). Fiji has experienced growing annual trade deficits, with the overall deficit rising from F$1.8 billion in 2010 to F$3.8 billion in 2019 (Fiji Bureau of Statistics, 2021). The total food import bill to Fiji averaged F$781.7 million over the five years from 2016 to 2020 (Fiji Ministry of Agriculture, 2021), and the nation's trade deficit in crop and livestock products was F$250.1 million in 2020 (Fiji Agriculture and Rural Statistics Unit, 2021). Formal beef production in Fijian abattoirs has fallen by at least 50 % since the industry's peak in 1971, and 'bush slaughtering' has increased (Duncan, 2010; Cole *et al.*, 2019). Domestic supply of beef accounts for only between 35 % and 50 % of annual domestic demand (Cole *et al.*, 2019), and at F$19.1 million in 2020, beef was in the top-10 imported agricultural commodities in 2020 (Fiji Ministry of Agriculture, 2021).

As detailed in Appendix A, average annual wood production from 2005 to 2020 had declined about 10 % relative to the average for the period 1987 to 2004. Furthermore, average value per cubic metre of log harvested has been declining, with pine (*P. caribaea* var. *hondurensis*) plantation logs destined for low-value woodchip export markets representing a higher share of output as native forest and mahogany (*S. macrophylla*) plantation sawlog volumes have declined (Fiji Ministry of Forestry, 2021a). Over the period 2013 to 2020, Fiji had an average annual trade deficit in timber and paper products of F$67.5 million.

Expansion of silvopastoral systems in Fiji could substantially reduce net imports, while also contributing to rural development objectives set in the strategic plans of the Ministry of Agriculture (2019) and Ministry of Forestry (2019), such as enhancing food security by 'mainstreaming' agroforestry, raising rural incomes from both farm and non-farm opportunities, increasing livestock and timber production, and encouraging adoption of sustainable resource management. Silvopastoral system adoption could also generate many environmental and socio-economic benefits, including reduced soil erosion, flooding, landslide and wildfire risk, and increased carbon stored on-site. There is also strong alignment of the expansion of silvopastoral systems with Fiji's contemporary development priorities, including:

- the Fiji 2020 Agriculture Sector Policy Agenda, which indicated increasing production of livestock products is a high priority in Fiji (Bacolod *et al.*, 2014; SPC Land Resource Division, 2016; Fiji Ministry of Agriculture, 2019).
- the Ministry of Agriculture's 5-year Strategic Development Plan (SDP) 2019-2023, where agroforestry is highlighted under strategic priority 3, 'Climate Smart Agriculture';
- contributing to Fiji's National Climate Change Policy 2018-2030, in which sustainable forestry is identified as a key priority, generating carbon benefits and co-benefits (e.g. biodiversity conservation, and flooding and landslide risk mitigation);
- Fiji's National Adaptation Plan (2018) for delivering on climate adaptation priorities, as well as emissions reduction contributions under the Paris Agreement, which calls for an expansion of agroforestry, and more sustainable land use practices on marginal sloping and coastal lands;
- the Low Emission Development Strategy 2018 to 2050, which aims to increase forest carbon storage through afforestation of an additional 77,400 ha;
- by improving fuel management on the landscape, silvopastoral systems can reduce wildfire risk, which will support efforts to earn results-based payments for increasing carbon sequestration and reducing carbon emissions from forest degradation, such as through the Forest Carbon Partnership Emissions Reduction Payment Agreement Fiji signed with the Forest Carbon Partnership Facility at the World Bank in 2021;

- contributing to the Fijian Trade Policy Framework 2015-2025, which highlighted agriculture and forestry as priority sectors through which Fijian exports can be diversified and earnings improved. Note that the economic benefits of increased livestock and timber production from silvopastoral systems arises irrespective of who consumes the food and timber. That is, regardless of whether it is exported, consumed at tourist resorts or by Fijians.
- contributing to the 30 million trees in 15 years (30MT15Y) program (Fiji Ministry of Forestry, 2019).
- contributing to the draft plan (not yet approved by the Government of Fiji) Horizon 2030, Fiji's Pathway to 'A Safe, Resilient, Innovative Food System' (September 2021) in which agroforestry is highlighted for its potential to increase access to healthy food and building resilience in the agricultural sector; and
- increase opportunities for the Ministry of Forestry to implement the May 2022 Standing Committee on Natural Resources (SCNR) second recommendation, which was: "Planted Forest Policy - The Committee recommends the Ministry to raise awareness and encourage the people to plant more trees".

Discussions with personnel from government and non-government organizations during the pre-project development trip in October 2016 and the project planning meeting in December 2018 revealed that the strong policy recognition of the need to improve management of degraded sloping land has not been translated into effective resourcing of necessary research and education or other support programs to implement change. Policy-makers lack information on the overall economic cost-benefit impact of management of this landscape. This research aimed to help address this gap.

The research team faced several challenges while performing this research. Changes to the administrative structure of the Fiji Ministry of Forestry in early 2019, followed by travel restrictions due to COVID-19 from early 2020 to early 2022, presented obstacles to achieving project sign-off in Fiji. This resulted in the budget being reduced by 70 % and the scope of the project being substantially compressed. The authors have had to employ desktop research methods, and there were few opportunities to collaborate with Fijian partners. Nevertheless, the research has delivered several valuable outputs that can support policy-development and guide future research with respect to Fiji's seasonally dry sloping lands. Policies, strategies and institutional settings relevant to agroforestry in Fiji were examined, opportunities, barriers and constraints were explored, and options identified for ways in which policy and institutional frameworks and instruments could include and facilitate the adoption integration of silvopastoral systems. A preliminary geospatial analysis has provided an estimate of land availability for silvopastoral systems on Viti Levu, and the necessary, software, datasets, procedures, costs, and required training for this estimation to be enhanced by in-country knowledge has been described. Guided by expert opinion and literature, a suite of potential silvopastoral systems for Fiji's sloping lands have been defined, the growth of pasture, livestock and trees simulated, and the financial performance evaluated from a leaseholder's perspective. Finally, an assessment of the broader socio-economic potential of silvopastoral systems in Fiji has been made. Limitations of the research and future research needs have been outlined.

4 Objectives

The project aim was to identify policy, institutional and governance options to encourage adoption of sloping land silvopastoral systems in Fiji, and provide decision-support information for government agencies, landholder communities and individual farmers on silvopastoral system design and expected financial and economic cost-benefit performance. The focus area is the seasonally dry sloping lands of western and northern Viti Levu and Vanua Levu. However, given limited project resources the research has focussed on Viti Levu, and the financial performance of silvopastoral systems has been estimated for a case study site northwest of Nadi. The project aim has been achieved by addressing the following objectives.

Objective 1. To examine the barriers and constraints to sloping land agroforestry in Fiji, and identify gender-inclusive policy and institutional frameworks and instruments to overcome these and facilitate the establishment of silvopastoral systems.

Objective 2. To identify potentially suitable combinations of pasture, livestock and tree species for silvopastoral systems on seasonally dry, sloping land areas on Viti Levu and Vanua Levu. Given large variation in previously published estimates of sloping land with agroforestry potential, this objective included a geospatial analysis to improve land availability estimates.

Objective 3. To collate production, cost and revenue data for individual tree and livestock species, and evaluate the financial performance (from a landholder perspective) of selected silvopastoral systems for alternative business models.

Objective 4. To develop and evaluate a regional-scale silvopastoral system adoption scenario.

5 Methodology

Methods are described for each research objective in turn. For objective 2, the geospatial analysis methods have been described separately from methods for tree species selection and silvopastoral system design.

5.1 Methods to examine policy barriers to silvopastoral systems, and institutional frameworks to overcome them

This research activity aimed to “examine the barriers and constraints to sloping land agroforestry in Fiji and identify options for gender inclusive policy and institutional frameworks and instruments to overcome these and facilitate the establishment of silvopastoral systems”. In undertaking this task, it was deemed necessary to identify and review the existing policy settings, to reveal the actors involved in agroforestry and distil key relationships and potential obstacles to the consideration of agroforestry in policy and policy processes.

In December 2018 the project team undertook a visit to Fiji for the purpose of project planning, to establish connections with key stakeholders and initiate research activities. While not specifically aimed at policy issues, several of the activities revealed areas of policy research interest and potential ‘hot topics’. The trip involved site visits, a two-day workshop, meetings with landholders and meetings with the Government, including the then newly appointed Permanent Secretary for Forests, Mr Pene Baleinabuli. Various presentations were made during the planning workshop including on key legal and policy issues. A trip report was produced.

A group Strengths, Weaknesses, Opportunities and Threats (SWOT) exercise was undertaken at the planning workshop. A SWOT analysis is a subjective assessment, and it was undertaken with the objective of reaching a shared view on favourable features and limitations of making greater use of Fiji sloping lands for crop, livestock and tree (CLT) agroforestry systems. Strengths are the outcomes that a project or activity is designed to achieve – basically the reasons for an activity or investment. Opportunities are favourable outcomes other than the core design benefits of the activity which might be possible. Weaknesses and threats approximate the constraints in achieving intended goals – what may be difficult to achieve, and what adverse outcomes are to be guarded against.

The workshop participants were asked to explore the question: what are the Strengths, Weaknesses, Opportunities and Threats to CLT agroforestry on sloping lands in Fiji? Participants first undertook a brainstorming exercise to list all strengths, weaknesses, opportunities and threats and were then asked to prioritise these, based on an allocation of 11 ‘points’ which they could assign to their most important issues (Figure 3).

Unfortunately, the constraints on the project due to COVID-19, meant that it was not possible to go to Fiji and talk to people about policies or to observe policy in action. This was unfortunate because policy and policy making is essentially a peopled process – policies are made by people, to change the behaviour of people. As such, broader literature on policy processes in Fiji was reviewed to conceptualise how, where and by whom policies are made in Fiji.

Thus, the method used in the research was primarily document-based. As Smith (2022) notes, analytic work on and with documents can be loosely divided into two areas:

a. work that focuses on the actual textual and extra-textual content of documents; and
b. work that focuses on some aspect of the use, role and function of documents in everyday and organisational settings.

Figure 3 The SWOT analysis at the project planning workshop in Suva, December 2018

The first focuses on the document as an object in its own right, the content of the document as static and immutable (Prior, 2008), as a 'docile' container of knowledge. The second area is primarily observational, seeking to understand some element of how documents are active agents in organisational and/or everyday life (Rapley and Rees 2018).

A desk-top review explored the ways in which agroforestry, and related issues and topics (e.g 'agriculture', 'forestry'), are described in Fijian policy documents, peer-reviewed literature and other relevant sources (e.g media). This also drew on the earlier ACIAR small research and development project (ADP/2014/013 *Promoting sustainable agriculture and agroforestry to replace unproductive land-use in Fiji and Vanuatu)* and a workshop, meetings and discussions during a project visit to Fiji in December 2018. We also drew on the conceptual research associated with another ACIAR Project in which two project team members (Smith and Kanowski) were concurrently involved, exploring the concept of policy in an investigation of 'research to policy impact' in Laos (SSS/2020/142). We draw on their methods and analysis to frame considerations of 'policy' in the Fiji context.

The approaches to document analysis adopted are detailed in Appendix B, but in brief this involved:

1. Reviewing the SRA report for ADP/2014/013 (Harrison and Karim 2016), and working papers developed for this project (FST/2016/147);
2. Re-examining the trip notes and outputs from the project's planning visit to Fiji in December 2018 to distil key themes;
3. Sourcing and re-reviewing the policy documents referred to in Harrison and Karim (2016) and the working papers, and sourcing and reviewing any newer policy documents produced since the working papers were drafted in 2019; and
4. Undertaking a search for and review of publications describing policy and policy processes in Fiji and distilling key features and learnings to guide recommendations with respect to barriers and constraints to agroforestry policy in Fiji.

5.2 Geospatial analysis to provide a preliminary assessment of land area suited to silvopastoral systems in Viti Levu

For this preliminary analysis, datasets included .jpg images from Google Earth (GE) and the National Aeronautical Space Administration (NASA) Fire Information for Resource Management (FIRM) system. Shuttle Radar Topography Mission (SRTM) images were also downloaded from NASA and processed with Arc GIS. The purpose of the analysis was to ascertain the location, area and nature of land which might best be used for silvopastoral systems. Because the area of Viti Levu is over one million hectares and the area of Vanua Levu is approximately half of that, it was not possible to conduct a full land use analysis of both islands. Hence a detailed investigation was confined in this case to Viti Levu.

GE and ArcGIS Earth were used to extract the following information:

- Topography and vegetation of the two islands;
- Areas of 'high rainfall' and 'rain shadow';
- Current land use;
- Evidence of annual grass fires; and
- Proximity of roads and tracks to potential agroforestry sites;

The FIRM data was used to corroborate the wide incidence of grass fires in the rain shadow areas. Using SRTM digital elevation models (DEMs), ArcGIS was used to extract datasets of terrain:

- Aspect (NE, SE, SW, NW);
- Elevation (meters asl); and
- Slope (degrees).

A typology of sites of potential suitability for agroforestry (or not) was then developed. Appendix C provides further details about: (1) datasets and Geographic Information System (GIS) software which would enable a spatial analysis of suitability of land on the islands of Viti Levu and Vanua Levu for agroforestry; (2) a preliminary aspatial analysis which indicates the way forward for an expanded investigation; and (3) the social, cultural and commercial considerations which could preclude or enhance opportunities for the take-up of any proposed agricultural improvements by farmers.

5.3 Tree species selection and silvopastoral system design for the case study analysis

5.3.1 Case study site for evaluation of silvopastoral systems

Historically, Tropical Dry Forest occupied much of the seasonally dry zones of western and northern Viti Levu and Vanua Levu that are the focus of this project (Keppel and Tuiwawa, 2007). More recent land practices have resulted in clearing of this vegetation or its destruction through regular wildfires. The vegetation of Fiji's sloping lands is now dominated by low quality grasses, shrubs, vines and tree species, referred to in some literature as the talasiqa lands (Morrison, 2019). Mission grass (*Cenchrus polystachios* syn. *Pennisetum polystachion*) is a fast growing, dominant, but low-quality pasture species found throughout this area (Aregheore, 2005). Unmanaged fields of mission grass are known to alter wildfire dynamics by providing high fuel loads for fires (Douglas *et al.*, 2004). Furthermore, the species can readily spread after fire. Grassfires represent a significant risk to tree planting within the study area (King, 2002; Conservation International, 2013). During the 2018 Project Planning Meeting, the project team were made aware of substantial areas of tree plantings lost to wildfire.

One of the potential demonstration sites for the originally proposed larger ACIAR project was a 500 ha parcel of rolling hill country near Nadi with Caribbean pine, illustrated in Figure 4. It is held under a long-term lease by Pastor Jacob, who has a willing workforce of parishioners and is enthusiastic about increasing the productivity of his land with agroforestry. The Pastor's land is broadly representative of seasonally dry sloping land in Viti Levu, and the design and evaluation of silvopastoral systems for this project have been performed with this case study site in mind. Climate statistics for Nadi are reported in Table 1.

Figure 4 The 500 ha case study site near Nadi held under a long-term lease by Pastor Jacob who is enthusiastic about agroforestry

5.3.2 Tree species selection

Fiji has a long history of agroforestry and tree planting programs for conservation and production purposes, with a wide range of tree species having been recommended (Clarke and Thaman, 1993; Elevitch and Wilkinson, 2000; Elevitch, 2006; Goswami and Singh, 2014; Harrison and Karim, 2016). Commercial plantations have been established by Fiji Pine Limited (*Pinus caribaea* var. *hondurensis,* https://fijipine.com.fj/), Fiji Hardwood Corporation Limited (mahogany: *Swietenia macrophylla*, https://www.facebook.com/FijiHardwoodCorporationLtd/?ref=py_c), and Future Forests Fiji limited (teak: *Tectona grandis*). Investment Fiji (https://www.investmentfiji.org.fj/) reported Fiji's hardwood plantation area (mainly mahogany) at 58,978 hectares, and the softwood pine plantation area at 76,171 hectares. However, Mr Ashwe (Operational manager, Tropikwood Fiji Ltd, part of the Fiji Pine Limited group of companies) indicated in 2022 the area of their lease actually planted to pine may be closer to 25,200 ha, with the rest of the lease area being inaccessible or native forest that can no longer be cleared for plantation development. Discussions with Mr Semi Dranibaka (Manager of Fiji Hardwood Corporation Limited) indicated the total area of hardwood plantation managed by Fiji Hardwoods in 2022 was about 41,000 ha of mahogany and 10,800 of other species, including eucalypts. The area of teak planted in Fiji is unclear. Agroforestry tree planting programs are wide spread across Fiji, with some of the better known examples including Nakauvadra community-based reforestation project (Conservation International, 2013), the Reforestation of the Degraded Foothills of the Sugar Belt (REFOREST) Project (https://www.spc.int/special-projects/sugar-projects/sugar-projects-fiji/reforest-project), Ridge to Reef project (https://www.pacific-r2r.org/) and 30 Million Trees in 15years (30MT15Y) (https://www.fiji.gov.fj/Media-Centre/News/Feature-Stories/30-Million-Trees-In-15-Years).

Table 1 Monthly average temperature and rainfall for Nadi, Fiji, adapted from Fiji Meteorological Service Records

Month	Ave. max. temp.	Ave. min. temp.	Rainfall (mm)	Rain days > 0.1 mm
January	31.6	22.7	299	18
February	31.5	23.0	302	18
March	31.1	22.6	324	19
April	30.6	21.7	163	12
May	29.8	20.1	78	7
June	29.2	19.3	62	6
July	28.5	18.3	46	5
August	28.7	18.4	58	5
September	29.4	19.3	77	6
October	30.2	20.4	103	9
November	30.9	21.5	138	11
December	31.4	22.1	159	13
Total			1809	

ACIAR site visits, trip report notes and discussions with experts and Fijian officials (K. Glencross pers. comm. 2014; L. Thompson pers. comm. 2015; P. Rokobiau and P. Bulai, Fiji Ministry of Forestry, pers. comm. 2015), as well as a broad literature review of published reports, and government and NGO websites was used to identify tree species that are currently promoted in tree planting programs in Fiji (Clarke and Thaman, 1993; Hald *et al.*, 1999; Sigaud *et al.*, 1999; Pouru, 2000; FAO and SPC, 2012; Conservation International, 2013; Padolina and Kete, 2014; Fiji Ministry of Forestry, 2021b). This revealed 98 native and exotic tree species that have been recommended for agroforestry and forestry systems in Fiji (please see Appendix D). Exotic species, such as conifers, eucalypts and acacias, were included because many have been show to grow satisfactorily on degraded sites and many have greater wildfire tolerance than native Fijian species (Harrison and Karim, 2016). With the exception of the major commercial species *P. caribaea* var. *hondurensis* and *S. macrophylla*, little information exists regarding species-site matching, growth rates or financial performance in Fiji.

The research proposal indicated that the Delphi survey method would be used to guide selection of suitable species for analysis, including gathering information about tree species growth and financial performance. This method has been used effectively for these purposes in Australian forestry research (Russell *et al.*, 1993; Harrison and Herbohn, 1996; Herbohn *et al.*, 1999). In brief, the method involves conducting opinion-based surveys of experts with knowledge of the tree species. Information is provided to the experts regarding the biophysical and climatic characteristics of the study area, and the experts are requested to provide their opinions regarding parameters of interest, such as growth rates and expected harvest ages. Opinions from the first round of the survey are collated, summarised and distributed back to respondents who are asked to reconsider their initial responses in light of the opinions of all experts. The aim is to improve the estimates, including addressing outlier responses. Sometimes obtaining responses from a third round may be warranted.

The Conservator of Forests in Fiji was approached to nominate staff within the Ministry of Forestry with technical expertise to participate in tree selection. However, officers from the Research Division were unable to participate, due to exceptional circumstances around

COVID-19 and their resulting reallocation of time to assist the Fiji Ministry of Health. A total of 23 experts listed in Appendix D were identified for invitation to participate in a Delphi survey to provide information on tree species growth within the study area in Fijian Government agencies, Australian and Fijian Universities, and Fijian non-government organisations. These experts were contacted via email and phone.

For two main reasons, the Delphi method was eventually rejected for informing tree species selection in the Fijian study area. First, few experts were willing and able to participate in tree species assessment. Of the 23 experts contacted, 11 accepted the invitation and participated in a first-round of species assessment. Of these, 4 were available to provide follow up comment in a second-round of species assessment. Second, the majority of experts had limited experience and knowledge on the growth and financial performance of many of the species, which meant that having multiple rounds of assessment would not generate useful data. Instead, one-on-one expert interviews were organised with experts via Zoom, phone and email.

Prior to the one-on-one expert interviews, a description of the study area (climate, rainfall pattern, geography) and the list of tree species revealed by literature review was provided. Experts were invited to add species that they believed warranted inclusion on the list, and to nominate other experts that they believed could assist in the technical assessment. Experts were requested to review the species list and identify those tree species capable of achieving a reasonable growth rate within the study area. For their identified species, the experts were then asked to provide information about growth and financial performance. It became apparent during this process that there is a dearth of published information and expert experience regarding growth and financial performance for the majority of the identified species for the study area. Consequently, many of the experts chose to provide a recommendation of 5 to 10 tree species that they were most confident would achieve reasonable growth, but they were not confident about providing quantitative estimates, except expected harvest ages.

Expert review of the list of species in Appendix D identified 44 tree species as capable of achieving a reasonable growth rate within the study area. A further 18 tree species were considered not capable of achieving a reasonable growth rate within the study area, and the remaining species were not assessed due to a lack of knowledge. The 13 species listed in Table 2 were identified by at least 2 experts as capable of achieving a reasonable growth rate within the study area.

Table 2 Frequency tree species was assessed as capable of achieving a reasonable growth rate within the study area

Rank	Tree Species	Frequency of recommendation
1	*Santalum* spp. (*yasi*, *album*, or *yasi* x *album*) (sandalwood)	7
2	*Pinus caribaea* var. *hondurensis* (pine)	6
3	*Corymbia citriodora* subsp. *citriodora* (spotted gum)	5
4	*Tectona grandis* (teak)	5
5	*Intsia bijuga* (vesi or merbau)	5
6	*Terminalia catappa*	4
7	*Swietenia macrophylla*	4
8	*Samanea saman* (*Albizia saman*)	3
9	*Morinda citrifolia*	3
10	*Leucaena leucocephala*	2
11	*Aquilaria* spp.	2
12	*Gliricidia sepium*	2
13	*Casuarina equisetifolia*	2

There was a relatively high degree of consensus among the experts, considering about 50 % agreed on all species in the top-five most recommended species. The top-five tree species were selected for silvopastoral system scenario development and evaluation. *Leucaena leucocephala* (hereafter simply referred to as leucaena) was also selected for inclusion due to its suitability as a host for sandalwood, and to provide an improved tropical pasture scenario, which would focus on livestock as a contrast to the silvopastoral system scenarios. Apart from *P. caribaea* var*. hondurensis* (pine) and *C. citriodora* subsp*. citriodora* (spotted gum), experts were unable to provide empirical data relevant for the study area.

5.3.3 Land use systems evaluated

A total of nine land use systems were evaluated, including the following five silvopastoral systems:

1. Sandalwood (*Santalum* spp.) with stylo (intermediate host) and leucaena (long-term host);
2. Pine (*Pinus caribaea* var*. hondurensis*);
3. Spotted gum (*Corymbia citriodora* subsp*. citriodora*);
4. Teak (*Tectona grandis*); and
5. Vesi (*Intsia bijuga*) and pine (*Pinus caribaea* var*. hondurensis*).

For comparative purposes, four alternative systems were designed for a total of nine scenarios:

6. Tropical pasture only (unimproved and no timber production);
7. Leucaena improved tropical pasture (no timber production)
8. Spotted gum with leucaena improved tropical pasture; and
9. Spotted gum timber plantation (no cattle production).

Tropical pasture only and leucaena improved tropical pasture are open paddock grazing systems without tree crops. The spotted gum with leucaena improved tropical pasture system is a combination of systems 3 and 7. The spotted gum timber plantation differs from the spotted gum silvopastoral system in that there is no cattle production and the stocking of final crop trees is double the silvopastoral system stocking.

Table 3 reports the management regimes for the five silvopastoral systems, including stems per hectare (SPH) planted and retained throughout the rotation. The remainder of this section outlines the modelled farm size, important analysis limitations, and provides a brief description of each system.

Farm size of modelled systems

On the basis of likely pasture productivity and the average cattle herd size of existing commercial beef producers in Fiji of about 70 adult equivalents (AE) (Cole *et al.* 2019), 200 ha (40 % of the area of Pastor Jacob's lease) was the adopted farm size for analysis of all non-sandalwood systems, because it was considered to be a scale at which silvopastoral systems could be commercially viable. The modelled farm size is large for Fiji, where only 3.4 % of households have a farm area greater than 10 ha (FAO and Fiji Ministry of Agriculture, 2021). According to Fiji Ministry of Agriculture (2021), there were 71,163 farming households in 2020, farming 194,768 ha (FAO and Fiji Ministry of Agriculture, 2021). However, the study area for this analysis is not recognised as agricultural land in Fiji. A sensitivity analysis has been performed to examine smaller farm sizes, including to estimate the minimum viable farm size for a cattle operation in the study area.

Table 3 Modelled systems: planting configurations, stems per hectare (*SPH*), changes in SPH due to thinning, and level of pruning

Management item	Silvopastoral system				
	Vesi and pine	Teak	Pine	Spotted gum [3]	Sandalwood [4]
Planting configuration in one replication [1,2]	Pa Pi V V Pi	Pa T T	Pa Pi	Pa Sp	Pa L L Sa Sa L L
Distance of pasture between replications (m)	10	10	8	10	6
Distance between rows if multiple rows in one replication (m)	Pine to Vesi: 4 Vesi to Vesi: 4	Teak to Teak: 2	n.a.	n.a.	Leucaena to leucaena: 0.75 Leucaena to sandalwood: 3 Sandalwood to sandalwood: 4
Distance between trees in a row (m)	Pine: 2.5 Vesi: 3	2.5	2.5	2.5	Leucaena: 2 Sandalwood: 5
Distance occupied by one replication (m)	22	12	8	10	17.5
SPH planted	Pine: 363 Vesi: 303 Total: 666	667	500	400	Leucaena: 1142 Sandalwood: 206 Total: 1348
SPH remaining after non-commercial thinning	Pine: 181 (year 4) Vesi: 100 (year 6)	200 (year 4)	250 (year 4)	200 (year 5)	n.a.
SPH pruned: 1st prune to 3 m	All pine (year 4 and vesi (year 6)	200 (year 5)	250 (year 5)	200 (year 5)	All sandalwood trees are pruned as necessary in years 1, 2, 3 and 4.
2nd prune to 6 m	Pine: n.a.; Vesi: 100 (year 15)	120 (year 8)	n.a.	120 (year 10)	Pruned to improve form, but not to a pre-determined height
SPH remaining after commercial thinning	n.a.	100 (year 12)	n.a.	100 (year 15)	n.a.
SPH harvested at clearfall	Pine: 181 (year 15) Vesi: 100 (year 40)	100 (year 25)	250 (year 20)	100 (year 30)	Sandalwood: 164 (year 26, due to mortality, including cattle damage)

Note: 1. Pa = pasture alley; Pi = row of pine; V = row of vesi; T = row of teak; Sp = row of spotted gum; L = row of leucaena; Sa = row of sandalwood.
2. The intermediate sandalwood host, stylo, is planted between the sandalwood rows in the sandalwood silvopastoral systems.
3. For the spotted gum plantation (no grazing) scenario, 300 SPH are retained after the non-commercial thinning and 200 SPH after the commercial thinning.
4. The same management applies for the sandalwood scenarios with and without the electric fence.

The sandalwood system was modelled at the scale of 20 ha. This was because it may not be technically or biophysically feasible to establish large areas of sandalwood in the study area, as well as the high investment costs per hectare and high labour requirement relative to all other modelled systems.

Important system analysis limitations: water, wildfire and cyclones

Cattle will require access to water year-round. Access to surface water is variable throughout the study area. Some farms may require limited investments in water infrastructure, while others may require large investments. The evaluation does not account for water infrastructure investment. It would be useful for future research in a larger project to consider water infrastructure requirements and costs.

Wildfire and cyclone risk has not been explicitly accommodated in the financial analysis. In a well-managed grazing system, cattle will reduce fuels and wildfire risk. All tree species were recommended by experts after considering several species selection criteria (see Appendix D), including resilience to wildfires and cyclones. It would be useful for future research in a larger project to consider methods to account for wildfire and cyclone risk in the evaluation of silvopastoral systems.

A major benefit of silvopastoral systems over timber plantations is the fuel management provided by livestock. In Australian silvopastoral systems, livestock are regarded as wildfire risk mitigation tool. The analysis has assumed intensive management of fuel until livestock are introduced to each of the systems, through slashing at least four times per year and pruning all trees. Even pine is pruned for this reason, although there is no market price premium for pruned pine logs in Fiji. This management of fuels will not prevent wildfire with certainty, but it will reduce the likelihood of catastrophic losses by greatly reducing wildfire severity. Spotted gum and pine in particular, will not be adversely affected by the low-severity wildfires that may burn in these silvopastoral landscapes after the trees achieve 10 cm DBH at age 5 to 6. On the other hand, sandalwood is always sensitive to fire. As silvopastoral systems expand in the study area, wildfire risk at the landscape-level will decline, because less of the landscape will be managed extensively for ‘green pick’ with annual to bi-annual burns for goats and other livestock.

Sandalwood, stylo and leucaena silvopastoral system

Two species of Sandalwood, the native *Santalum yasi* and exotic Indian sandalwood *Santalum album*, as well as a hybrid *S. album* × *S. yasi* were observed as commonly planted in Fiji during the 2018 pre-project planning field trip. Contrary recommendations were provided during engagement with experts regarding the choice of sandalwood species to grow in the study area. Concerns were expressed about genetic conservation of the native sandalwood, with some experts recommending only the native sandalwood be considered for planting. Advice was also provided from experts that it is too late to prevent further hybridisation with *S. album*, and therefore it does not matter which species is planted. The *S. album* × *S. yasi* hybrid has been reported as typically having superior growth rates to *S. yasi* (Bush *et al.*, 2020). For the purpose of this study, a generic sandalwood species (*Santalum* spp.) has been assumed.

Cattle will preferentially graze the long-term sandalwood host in this system, leucaena. To protect both the leucaena and sandalwood from over-browsing by cattle, the 20 ha planting has been modelled as four fenced 5 ha cells through which the livestock are rotated.

Sandalwood is recognised as particularly sensitive to fire, which means careful fuel management is required throughout the rotation. The introduction of livestock when trees grow above browse height has been recommended as one approach to reduce fuel loads and wildfire risk (Forest Products Commission, 2018), although there is limited published evidence of sandalwood being grown as part of a silvopastoral system (Gillieson *et al.*, 2008; Stephens *et al.*, 2020); https://www.abc.net.au/news/rural/2021-01-31/sanatol-ditchespesticide-for-goats-in-sandalwood-weed-trial/13103134). A cautious approach to the introduction of livestock has been modelled. In the sandalwood scenario without an electric fence protecting each row of sandalwood trees, cattle are introduced in year 10 when the trees are expected to have a basal diameter of 7 cm under the growing conditions of the study area. At this age, it is assumed that the sandalwood trees will be sufficiently tall and robust to avoid significant damage from cattle. This report also evaluated a sandalwood silvopastoral system with electric fencing to assess the benefits of introducing cattle in year 2. As experience is gained in grazing under sandalwood, the choice of livestock and the timing of livestock introduction may require adjustment relative to the scenarios modelled.

Sandalwood is a hemiparasitic species that requires hosts during all stages of growth for nutrient requirements and to sustain vigorous plant growth. The hosts are typically reported for three different life stages of sandalwood, being; a pot host, intermediate host and long-term host (Page *et al.*, 2012b). According to Page *et al.* (2018), *Stylosanthes* spp. (stylo) is a forage legume that may be considered an intermediate sandalwood host in a controlled grazing system. Leucaena has been found to perform well as a long-term sandalwood host (Page *et al.*, 2018; Rome *et al.*, 2020), although Page *et al*. (2018) noted that sandalwood growth may be impaired due to the vigorous growth of leucaena if the shrub is not heavily pruned. The stylo has forage benefits for cattle and, as a forage legume, leucaena provides high quality feed for livestock that increases live weight gain per animal or carrying capacity per hectare, compared to grass only pasture. leucaena has been recorded as an invasive weed in the study area (Conservation International 2013), and a number of experts contacted did express concern with promoting its planting due to its ability to form dense infestations. Considerable plant breeding has occurred with leucaena around the development of psyllid-resistant varieties and, more recently, efforts to produce sterile varieties (Real *et al.*, 2019). It would be a question for Fijian authorities as to whether fertile leucaena would be permitted for establishment within the study area before sterile varieties become commercially available.

Pine silvopastoral system

The main product coming from Fiji's existing pine plantation estate is woodchip for export. The pine silvopastoral system has been modelled over a 20-year rotation that is maintained at a relatively high stocking of 250 SPH in the expectation that much of the volume will be for woodchip. There will be a greater loss of pasture production in this system than most of the other systems because of high tree stocking, but this is offset somewhat by a shorter timber rotation.

Walkden-Brown and Banks (1986) reported the limited development of pine and livestock silvopastoral systems in Fiji, with experiments showing that returns from cattle did not cover costs. Investigations into pine silvopastoral systems by the Fiji Pine Commission in the early 1980's concluded that given high overhead costs, commercial cattle grazing on unimproved pasture under pines, is an unlikely prospect (Drysdale, 1982 reported in Clarke and Thaman, 1993). Walkden-Brown and Banks (1986) and Clarke and Thaman (1993), both reported on reduced wildfire risk from fuel load reduction associated with grazing under pine. Despite these earlier studies, interest continues to be expressed about the potential for pine-based silvopastoral systems, and several experts interviewed called for further research on the profitability of pine silvopastoral systems in Fiji.

Spotted gum silvopastoral system

A replicated, multi-species, but unmanaged trial of native and exotic timber trees in a part of New Caledonia that has an average annual rainfall of less than 1000 mm, and experiences cyclones and wildfires, revealed that spotted gum was the stand-out performer at age 37 (Figure 5, Associate Professor David Lee, University of the Sunshine Coast, personal communication February to April 2022).

There appears to be little experience in growing *Eucalyptus* and *Corymbia* species in Fiji. Fiji Ministry of Forestry staff identified two *Eucalyptus* trials during the 2018 project planning meeting and fieldtrip. At one site near Lautoka, a 3-year-old trial planting consisting of: *E. pellita*, *E. cloeziana*, *E. camaldulensis*, *Pinus* spp., *Acacia* spp., and teak was observed. However, competition from weed species make it difficult to infer species performance from this trial. A second site near Nadi, managed by the Pacific Island Rainforest Foundation contained a 3-year-old planting of *E. camaldulensis*, *E. grandis* and *E. deglupta*. A wildfire in the first year killed the *E. grandis* and *E. deglupta*, while *E. camaldulensis* had resprouted from the base and most trees at the time of our visit were over 2.5 m tall with multiple leaders.

Figure 5 An unmanaged 37-year-old spotted gum stand on sloping land in New Caledonia

Source: Associate Professor David Lee, University of the Sunshine Coast.

During the project planning fieldtrip, the project team heard concerns about incorporating eucalypts into silvopastoral systems from Mr Adrian Joseph Ram, Chief Executive Officer, Yaqara Pastoral Company, who considered eucalypts to be toxic to animals and to have negative effects on the soil. Marika Tuiwawa (University of the South Pacific) expressed concerns about the reputation of eucalypts for negative hydrological impacts and 'drying the land'. During a meeting with a Fijian sawmiller in 2018, the authors learned that Fijian sawmills have experienced poor recovery of sawnwood from locally-grown, young (less than 15 years) plantation *Eucalyptus* logs, which has given Australian species in Fiji a bad reputation among sawmillers.

In eastern Australia, spotted gum forests have been managed as silvopastoral systems with cattle for over a century (e.g. Figure 2), and the timber is highly desired by Australian industry for electricity distribution poles, decking, flooring, structural applications and furniture. Energy Fiji Limited (EFL) files annual orders with Australian sawmills for hundreds of *Eucalyptus* and *Corymbia* electricity distribution poles (15.5 m to 17.0 m) and thousands of hardwood cross-arms for overhead sub-transmission systems (3.5 m to 6.0 m), and one of

EFL's preferred species is spotted gum (personal communication with sawmill managers in southern Queensland, April to June 2022). In 2022, the price of 15.5 m poles delivered to Fiji was in the order of A$1900 (F$2850) per treated pole. On good sites, Australian *Eucalyptus* and *Corymbia* species can achieve a sawlog size in 15 to 20 years. Logs from such young trees can be used in the round; however, experience in Australia indicates significant growth stresses in young trees, resulting in low recovery of sawn wood (Venn *et al.*, 2020). The spotted gum silvopastoral system has been modelled over a 30-year rotation, which is considered sufficient to minimize growth stresses.

Spotted gum is the only modelled tree species for which seed would have to be imported. There is a ready supply of improved seed from select trees in Australia (contact Associate Professor David Lee at the University of the Sunshine Coast). Seedlings are easy to propagate and trees are highly resilient to wildfire. Spotted gum generally has good bole form and naturally sheds lower branches. The final stocking of 100 SPH balances timber production with pasture production.

Teak silvopastoral system

Under wide tree spacing, teak can develop poor form with large lateral branches and forked stems (Associate Professor Mark Dieters, The University of Queensland, personal communication, May 2022). This was observed in 5-year-old teak trees at the Nakauvadra Community Based Reforestation Project in 2015. Dr Lex Thomson (personal communication, 2015) noted that teak tree form associated with wide spacing also results in teak being more susceptible to damage during cyclones. Pachas *et al.* (2019a; 2019b) reported that in Colombian silvopastoral systems with teak, double and triple rows of teak trees separated by pasture alleys of 8 m to 25m have been trialled to improve tree form. The analysis of the teak silvopastoral system in the study area assumes a double-row of teak separated by only 2 m, and 2.5 m between trees within a row. It is expected that this would promote improved tree form by discouraging large lateral branching. The final tree stocking of 100 SPH is achieved at age 12, and the trees would be clearfelled at age 25.

Vesi silvopastoral system

Vesi is a native tree species to Fiji and heavily promoted in many conservation and reforestation tree planting programs. Observations were made of the performance of 5-year-old vesi at the Nakauvadra Community Based Reforestation Project in 2015. It was noted that all specimens of vesi were multi-stemmed, and requiring heavy form pruning. Dr Lex Thomson (personal communication, 2015) recommended that, when vesi is planted for timber production, it should be planted into a 'light well' created by adjacent faster-growing species. That recommendation has been applied in the modelled vesi silvopastoral system. *P. caribaea var. hondurensis* was adopted as the fast-growing companion species. While a positive influence on young vesi growth and form, it is anticipated that overcrowding by pine will occur. Clearfelling of pine of pine at age 15 is designed to free up site resources. Vesi is modelled as being planted as double-rows 4 m apart to promote improved tree form by discouraging large lateral branches. Thaman *et al.* (2006), reported that only early growth data are available, and growth rates of older trees are not known. The expert interviews revealed considerable uncertainty regarding rotation length for vesi in the study area, with responses varying from 40 to 120 years. This analysis has adopted a 40-year rotation, which is 10 years longer than for any other modelled system. The rationale for choosing the low-age end of the clearfall harvest range was that, if vesi generates a poor financial performance over a 40-year rotation, it is likely to be even less financially viable over longer rotations, unless there is a large stumpage price premium paid for larger logs from older trees.

Tropical pasture only system (unimproved and no timber production)

The case study area is dominated by mission grass and other low-quality pastures, which contribute to poor beef productivity in Fiji (Aregheore, 2005; RESCCUE, 2018). Skerman and Riveros (1990) reported that young mission grass is palatable to livestock, but that older mission grass can be "completely inedible straw" that stock avoid. However, with sound grazing management that prevents mission grass from going to seed, the palatability and nutrition value of the grass can be maintained (Skerman and Riveros, 1990). There is disagreement in the literature about whether it is financially viable to fertilise mission grass in Fiji (Skerman and Riveros, 1990; Aregheore, 2005). Published information about mission grass dry matter production relevant to the study area are limited. Skerman and Riveros (1990) cited a Partridge (1975) study at Sigatoka, where fodder production of between 800 kg DM/ha and 1500 kg DM/ha was produced monthly between January and May, but between 0 kg DM/ha and 500 kg DM/ha was produced monthly for the rest of the year. Aregheore (2005) reported that unmanaged mission grass pasture in Fiji can produce 6000 kg DM/ha per annum, but is silent about what fraction of this is palatable.

In all systems evaluated, mission grass is assumed to dominate pasture production. It is also assumed that the cattle are managed to reduce the proportion of mission grass going to seed and becoming unpalatable. Constant grazing by cattle will also keep fuels on the landscape low, reducing wildfire risk. The pasture production model described in section 5.4.3 and Appendix G assumes net palatable pasture production of 2662 kg DM/ha/y when there is no competition with trees.

Leucaena improved tropical pasture system

The 200 ha farm would be divided into ten fenced 20 ha paddocks to facilitate cell grazing of pasture and leucaena. Given that the optimal benefit from leucaena is achieved when it represents about 40 % of cattle diet (Dalzell *et al.* 2006), this scenario was designed to achieve that proportion through analysis of pasture production with leucaena and as open pasture only. Recommended leucaena row spacing and planting designs are not available for Fiji. The recommendations of Dalzell *et al*. (2006), for dryland plantings of leucaena in Australia are twin rows (50–100 cm apart) at 6–8 m centres. This analysis assumed 6 m between leucaena double-rows, with the rows planted 0.75 m apart. Narrower spacing between the double rows results in excessive shading and reduced pasture production. The twin row planting is recommended to reduce the size of individual leucaena plants, which produces finer stems with a high proportion of leaf (Shelton *et al.* 2021).

Spotted gum with leucaena improved tropical pasture

This system was designed to optimally combine leucaena with spotted gum over an investment period of 30 years. The 200 ha farm would be divided into ten fenced 20 ha paddocks to facilitate cell grazing of pasture and leucaena. Given that the optimal benefit from leucaena is achieved when it represents about 40 % of cattle diet, this scenario was designed to achieve that proportion through analysis of pasture production under spotted gum and with leucaena. It was found that this proportion was achieved while maximising the present value of financial returns from cattle and timber when 12 ha of each 20 ha cell was managed as spotted gum silvopasture, and the remaining 8 ha planted to leucaena, as described in the leucaena improved tropical pasture system.

Spotted gum timber plantation (no cattle production)

This system was assumed to be planted at 400 SPH (5 m x 5 m spacing). Silviculture timing is the same as for the spotted gum silvopastoral system in Table 3; however, the non-commercial thinning reduces the stand to 300 SPH in year 5, and the commercial thinning in year 15 reduces the stand to 200 SPH.

5.4 Financial evaluation of silvopastoral systems

This section begins with a method overview. Next the methods to estimate the growth, costs and returns to tree growing is described. Finally, the cattle herd management mathematical model is outlined.

5.4.1 Method overview

The silvopastoral systems evaluated involve the joint production of trees, pasture and livestock on the same land units. The financial performance of these systems was estimated in a four-step procedure:

1. Estimate the net present value per hectare (NPV) of one rotation of the tree crop, *NPVTC*. The present value of the costs of land preparation, planting and ongoing management costs, were subtracted from the present value of the returns from the sale of logs. This step is described in detail in section 5.4.2.
2. Estimate the NPV per hectare of cattle production over one rotation of the tree crop, *NPVCP*. The present value of the costs of managing a cattle herd, including fences and cattle yards, were subtracted from the present value of the returns from the sale of cattle. The negative impact of tree growth on pasture production is accommodated in the analysis. This step is described in detail in section 5.4.3.
3. Estimate the NPV per hectare for the silvopastoral system (*NPVSPS*) by summing *NPVTC* and *NPVCP*, and subtracting the present value of lease establishment fees (*EF*, paid in year zero only) and annual lease (*AL*) payments.

$$NPVSPS = NPVTC + NPVCP - EF - \frac{AL}{r} \quad (1)$$

where r is the real (net of inflation) discount rate (%)

4. To facilitate comparison between silvopastoral systems of different tree rotations, estimate the land expectation value per hectare for each silvopastoral system (LEV) as follows

$$LEV = NPVSPS + \frac{NPVSPS}{(1+r)^t - 1} \quad (2)$$

where t is one tree rotation for the silvopastoral system (years). For the tropical pasture only and leucaena improved tropical pasture, t was set to 30 years.

EF per application to the iTaukei Land Trust Board (TLTB) were estimated at F$3815 (https://www.tltb.com.fj/Payment-Options/Schedule-of-Fees). These are the application, processing, documentation, and de-reservation fees appropriate for forestry, gravel and mining applications[1]. *AL* payment to landholder (F$11/ha) and administration charges payable to TLTB (F$1/ha) are estimated to amount to F$12/ha/y (Xing and Gounder, 2021; Fiji Bureau of Statistics, 2022; Pratibha, 2022). Annual lease costs for agricultural land can be much higher, ranging from F$45/ha/y to F$480/ha/y (Prasad *et al.*, 2020).

The discount rate is of critical importance in a cost-benefit analysis, representing the time preference for money and opportunity cost of capital. In subsistence economies, the time preference for money can be high. For example, Teh *et al.* (2014) estimated the average annual nominal discount rate of small-scale fishers in Fiji is 208 %. At that rate, $1 next year

[1] *Fees for residential and agriculture applications are half the fees payable for forestry applications; however, the lease establishment fees reported by Enterprise Challenge Fund (2013) for community-based Fijian teak plantations are similar to the high-cost forestry, gravel and mining application fees. Therefore, the higher cost forestry application fees have been adopted in this analysis.*

is worth only $0.48 today, and only investments providing high returns within a short timeframe would be financially viable. Ota *et al.* (2022) evaluated the financial performance of sandalwood plantations in Vanuatu with discount rates based on commercial lending rates of 10 % to 28 %. The most commonly used real discount rate for development projects in the South Pacific is 10 % (Page *et al.*, 2010; O'Garra, 2012), although renewable energy projects in Fiji have been evaluated with real discount rates of 3 % to 6 % (Charan, 2014; Nair and Kumar, 2020). Brown and Daigneault (2014a, b) recommended using 8 % for long-term environmental management projects in Fiji. Improved management of seasonally dry and degraded sloping lands in Fiji will generate broader societal benefits that go beyond returns to the farmer. In recognition of this fact, and that successful establishment of financially viable silvopastoral systems in Fiji will require long-term partnerships between traditional land-owning groups, farmers, the Fijian Government, non-government organisations and sources of foreign aid, a real (net of inflation) discount rate of 8 % has been adopted in this study. The sensitivity of LEV to the discount rate has been investigated in this study.

5.4.2 Estimating the growth and financial performance of tree crops

NPVTC has been estimated as follows.

$$NPVTC = \sum_{t=0}^{T} \frac{(CS_t \times CHV_t + TS_t \times THV_t) - \sum_{a=1}^{A}\left((LC + OC_a) \times LH_{at}\right) - (SC \times SPH_t) - \frac{ToolC_t}{HA}}{(1+r)^t} \quad (3)$$

Where CS_t is stumpage price of logs at clearfall (F$/m^3);

CHV_t is the clearfall harvest volume (m^3/ha);

TS_t is the stumpage price of logs at commercial thinning (F$/m^3);

THV_t is the commercial thinning harvest volume (m^3/ha);

LC is the wage paid to labour (F$/hour);

OC_a is the non-labour operating cost of equipment (F$/hour);

LH_{at} is the labour hours required (hours/ha);

SC is the seedling cost for the tree species (F$/seedling);

SPH is stems per hectare planted;

$ToolC_t$ is the cost of tree management tools (F$);

HA is the area of tree planting (ha);

r is the real (net of inflation discount rate (%);

t is an index set for time in years since establishment of the primary tree crop(s) in year zero. In the sandalwood without electric fence scenario, the leucaena is established four years after the sandalwood and stylo; and

a is an index set for silvicultural activities.

Planting configurations, as well as thinning and pruning targets for the silvopastoral system scenarios are reported in Table 3. The individual tree growth and merchantable volume functions reported in Table 4 and Appendix E were used to estimate CHV_t and THV_t. Table 5 summarises cost and revenue parameters for financial analysis of tree crops (CS_t, TS_t, *LC*, OC_a, *SC*, and $ToolC_t$). Appendix F details the year (*t*) and labour requirements LH_{at} for silvicultural operations.

Table 4 Individual tree growth and merchantable volume functions with which THV_t and CHV_t were estimated

Individual tree characteristic	Tree species				
	Vesi [1]	Teak [2]	Pine [3]	Spotted gum [1]	Sandalwood
DBH over bark (cm)	$0.0001Age^3 - 0.0229Age^2 + 1.8816Age - 1.4432$	$60(1-e^{-0.07Age})^{1.165} \times 0.8$	DBH under bark equation in Allen (1991)	$2.0208Age – 0.0227Age^2$	Basal diameter (BD), not DBH 0.7Age
Height (m)	$-0.0051Age^2 + 0.798Age$	$35(1-e^{-0.09Age})^{1.1} \times 0.8$	$2.0463Age - 0.0386Age^2$	$1.7378Age - 0.0194Age^2$	na
Merch Ht (m)	0.33Height	dob=4.83+Hd/0.99 Hh=7.768+0.725Height+0.293Age +0.13DBH. Merch Ht is Hh where Hd is 7 cm, based on the taper equation.	na	0.33Height	na
Taper	0.5 cm/m	(DBH-dob at Hh)/(Hh – 1.3 m) ~ 1.24 cm/m	na	0.5 cm/m	na
Bk thick. (BT)	1.03 cm	dub=dob x 0.99 – 4.83	na	1.03 cm	na
Merch. Vol (m^3) and Sandalwood heartwood yield (kg)	$0.5((DBH-2xBT)/200)^2$ x pi + (DBH-2xBT-((Merch Ht – 1.3) x Taper))/200)^2 x pi) x Merch Ht	0.5(cross-sectional area under bark at breast height + cross-sectional area under bark at Merch Ht) x Merch Ht	Cross-sectional area under bark at breast height x Height x 0.4	$0.5((DBH-2xBT)/200)^2$ x pi + (DBH-2xBT-((Merch Ht – 1.3) x Taper))/200)^2 x pi) x Merch Ht	2.97BD - 27.0
Source	Developed for this project from limited published data from Samoa, Indonesia, Papua New Guinea and Malaysia	The 80 % growth performance model for Costa Rica by Pérez and Kaninen (2005) for DBH and Height. Diameter over bark (and under bark) and merchantable height were estimated with eq. (8) and (6), respectively from Moya *et al.* (2020) for teak plantations in Costa Rica.	Long diameter equation for Fijian *Pinus caribaea* plantations (Allen, 1991). Height from Dieters and Brawner (2007) for *P. caribaea* plantations in southern Queensland	Developed for this project from limited unpublished data provided by David Lee, University of the Sunshine Coast, for 37 year-old unmanaged trials in New Caledonia.	Basal diameter growth Tony Page (Personal Communication, March 2022). Heartwood yield from for Vanuatu plantations (Page *et al.*, 2012a).

Notes: 1. The DBH and total tree height models developed for vesi and spotted gum are illustrated in Appendix E.
2. dob is diameter over bark; Hd is heartwood diameter; Hh is height where heartwood diameter is zero; dub is diameter under sapwood for teak.
3. The Merch Vol. function did a remarkable job representing Nadi *P. caribaea* plantation individual tree volumes published by Cown (1981). For example, Cown (1981) reported individual tree volumes over a range of harvest ages, including 0.43 m^3 at 13 years and 1.02 m^3 at 24 years, respectively. The Merch. Vol function adopted estimated the individual tree volumes as 0.40 m^3 at 13 years and 0.99 m^3 at 24 years.

Table 5 Cost and revenue parameters for financial analysis of tree crops

Parameter	Notation	Unit	Amount
Discount rate	*r*	%	8
Labour cost	*LC*	F$/hour	4
Tool cost: axe, brush hook, telescopic pruning saw, clearing saw, arborist chainsaw, personal protective equipment [1]	$ToolsC_t$	F$/farm	4535
Non-labour operating cost of clearing saw and arborist chainsaw [2]	OC_a	F$/labour hour	1
Seedling costs at planting and infilling (5 % of seedlings are assumed to die and require infilling) [3]	*SC*	F$/seedling	
		Vesi	3.0
		Teak	3.0
		Pine	1.5
		Spotted gum	2.0
		Sandalwood	6.0
		Leucaena	1.5
Commercial thinning timber revenues [4]	TS_t	F$/m^3	
		Teak	100
		Spotted gum	50
Clearfall timber revenues [4]	CS_t	F$/m^3	
		Vesi	250
		Teak	250
		Pine	50
		Spotted gum	150
		F$/kg	
		Sandalwood	75

Sources: 1. Average of several rural farm supply store quotes.
2. Expert opinion from Australian forestry services provider.
3. Seedling costs for teak and vesi were provided by Apisi Rimamalo, Divisional Forest Officer Western Division, Fiji Ministry of Forestry in 2022 and Enterprise Challenge Fund (2013). Sandalwood seedling costs from Ota *et al.* (2022). Pine, spotted gum and leucaena seedling costs are estimates made by the project team.
4. Stumpage prices adopted are justified in the text below.

Stumpage price justification

Sandalwood

Bolatolu *et al.* (2022) estimated the financial performance of sandalwood plantations in Fiji using a price of US$46/kg (F$100/kg) for de-sapped heartwood. In the same publication, Ota *et al.* (2022) performed a financial analysis of sandalwood farming in Vanuatu, and used a 'most likely' weighted sandalwood heartwood price of US$22.4/kg (F$49.4/kg)[2]. Conservation International (2013) reported local Fijian market prices of around F$85/kg to F$100/kg. The average reported sandalwood price in in the Fijian market over the period 2012 to 2018 was F$103.8; however, this statistic hides the enormous variability in recorded average annual prices, which ranged from F$12/kg in 2016 to F$208.72/kg in 2015 (Bolatolu *et al.*, 2022). Average prices from 2012 to 2015 were F$147.4/kg, while average prices for the period 2016 to 2018 were F$45.7/kg (Bolatolu *et al.*, 2022). Bolatolu *et al.* (2022) suggested this price reduction was likely, at least in part, due to declining sandalwood quality. Personal communication in 2022 from Apisai Rinamalo, Divisional Forest Officer, Ministry of Forestry, indicated farmgate prices for sandalwood in Fiji range between about

[2] *The price was weighted assuming 5 % of harvested heartwood was suitable as craftwood with a value of US$30.7/kg, and 95 % of the heartwood was for oil production, valued at US$21.9/kg.*

F$50/kg and F$100/kg. A price of F$75/kg has been adopted for this analysis, and the sensitivity analysis performed does capture a price level consistent with that adopted by Ota *et al.* (2022) for Vanuatu.

Pine

There is a high volume of plantation pine logs harvested and traded annually within Fiji. The General Manager of Fiji Pine Limited, Asesela Cokanacagi, asserted that a 20-year rotation is common and that mill-gate prices for pine sawlogs, poles, pulp and posts are F$91.3/m^3, F$74.6/m^3, F60/m^3 and F$55.1/m^3, respectively. Personal communication in 2022 from Apisai Rinamalo, Divisional Forest Officer, Ministry of Forestry, indicated farmgate prices for pine logs range from F$20/m^3 to F$50/m^3. This analysis has adopted F$50/m^3 on the expectation that, at the wide spacing adopted for silvopastoral systems, a higher proportion of trees harvested at 20 years will be of a sawlog size and thus achieve a relatively high stumpage price.

Spotted gum

Typical stumpage prices for native forest spotted gum sawlogs and electricity distribution poles in Queensland are A$120/m^3 and at least A$150/m^3 (F$181/m^3 and F$227/m^3), respectively (Venn, 2020; Venn *et al.*, 2021; Francis *et al.*, 2022). In 2022, sawmills in Queensland were willing to pay stumpage of A$240/m^3 (F$360/m^3) for large (50 cm DBH) native forest spotted gum sawlogs that will yield high proportions of decking and flooring (Personal communication with sawmill manager in southern Queensland in March 2022). An average clearfall stumpage price of F$150/m^3 has been adopted, and the stumpage price for small poles and wood chip from a commercial thin at age 15 was assumed to be F$50/m^3.

Teak

Teak is a widely traded tropical timber, and Fijian plantation teak stumpage prices are unlikely to exceed world plantation teak prices. Therefore, plantation teak stumpage prices in Fiji are unlikely to be between F$500/m^3 and F$996/m^3 at clearfall, as asserted in several non-government Fijian publications (Blyth and Siwatibau, 2013; Conservation International, 2013; Enterprise Challenge Fund, 2013; Booth *et al.*, 2018). In global timber markets, mill-delivered teak log prices can range from US$200/m^3 to US$1000/m^3, but the higher end of this range is reserved for large logs from natural forests (Kollert and Kleine, 2017; ITTO, 2020).

In the *Global Teak Study*, Kollert and Kleine (2017) explained that the strong reputation of teak was built from high quality timber from natural forests in India, Lao PDR, Myanmar and Thailand. Wood from teak plantations greater than 50 years of age in India, Thailand and Indonesia can be commensurate with the quality of teak from native forests. But global teak markets make a fundamental distinction between teak grown in natural and planted forests. Logs from natural forests typically have a considerable log size advantage with a much higher proportion of heartwood. Beyond log size and proportion of heartwood, there are strong market perceptions that native teak logs have better properties than plantation teak. Short-rotation plantation-grown teak does not have a reputation as a quality product on the international market. For example, sawnwood from plantation teak in Myanmar is exported to India (the world’s largest market for teak) at a price per cubic metre that is 25 % to 50 % of the price of sawn teak from large natural forest logs in Myanmar (ITTO, 2020).

Kollert and Kleine (2017) conducted a financial analysis of a teak plantation in Ghana managed on a 25-year rotation with export of logs to an unspecified market and assumed a stumpage price[3] of US$70/m^3 to US$130/m^3 (F$150/m^3 to F$287/m^3) for squared logs with

[3] The analysis assumed a market price of US$250/m3 of log, but the analysis included costs of $120/m3 to $180/m3 for harvest, haul, certification and port charges for squared logs (sapwood removed), which need to be deducted from the market price to estimate the stumpage price.

sapwood removed. On the basis of mill-delivered plantation teak prices in Brazil reported by Consufor (2017) for logs with the diameter under bark expected at age 25 in Fiji (30 cm to 35 cm), and then subtracting Fijian harvest, haul and logging license costs of F$53/m^3 (Enterprise Challenge Fund, 2013), a stumpage price in Fiji consistent with global markets could be about F$163/m^3 to F$293/m^3. Personal communication in 2022 from Apisai Rinamalo, Divisional Forest Officer, Ministry of Forestry, indicated farmgate prices for teak logs with sapwood are likely to be about F$150/m^3 to F$200/m^3. For the analysis, a stumpage price for small teak poles at age 12 was set at F$100/m^3, and the clearfall price for 25-year sawlogs was set at F$250/m^3 of heartwood. The adopted clearfall stumpage price is consistent with a total log volume price at the upper end of the range recommended by Apisai Rinamalo.

Vesi

Vesi is a globally traded timber species. Published stumpage prices in Asia and the Pacific range from US$3/m^3 to US$70/m^3 (F$6.60/m^3 to F$155/m^3) (Tong *et al.*, 2009; Fox *et al.*, 2011; Laurance, 2012; Scudder *et al.*, 2019). For example, on Malekula, Vanuatu, Carodenuto *et al.* (2017) reported stumpage prices of US$21/m^3 (F$47/m^3). Personal communication in 2022 from Apisai Rinamalo, Divisional Forest Officer, Ministry of Forestry, indicated farmgate prices in Fiji for vesi logs are likely to be about F$75/m^3 to F$80/m^3 (~US$36/m^3). The Manager of Valebasogo Tropikboard in Labasa, Vanua Levu, indicated their company paid F$45/m^3 stumpage for native forest vesi logs (personal communication 2022). However, for the months of November and December 2019, China Customs data revealed that the average imported vesi log prices were US$395/m^3 and US$439/m^3, respectively (ITTO, 2020), which suggests high rent capture by logging companies. There is strong evidence of large quantities of unsustainably and illegally harvested vesi entering international trade from forests in Asia and the Pacific, which would also act to depress stumpage prices for legally traded logs of this species (Tong *et al.*, 2009; Shearman *et al.*, 2012; Riddle, 2014; INTERPOL, 2019; Anon., 2020; Ng *et al.*, 2020).

In Queensland, Australia, imported sawn vesi has high market acceptance, which has capped the wholesale price for domestically produced spotted gum flooring and decking (personal communication from several sawmill managers in southern Queensland in 2022). This suggests Australian sawmills could be willing to pay a similar stumpage price for vesi logs as they do for spotted gum (A$120/m^3; F$181/m^3) if it was sawn in Australia. China is willing to pay about US$420/m^3 for imported native forest vesi logs (ITTO, 2020). Subtracting the harvest and freight costs reported by Kollert and Kleine (2017) for teak (described above), would suggest a potential stumpage price of native forest vesi logs (that is presently largely captured by the logging companies) of US$240/m^3. Assuming plantation logs will be lower quality than native forest logs, and adopting a 50 % stumpage price penalty, plantation vesi stumpage price could potentially be US$120/m^3, which is about F$250/m^3. That price has been adopted in this study. Some may consider this an optimistic price, but the supply of this species from natural forests is declining, and this will eventually reduce the supply of illegal logs and potentially facilitate greater returns to growers. Also, if vesi plantations are not financially competitive at this price in the study area, then this could provide a sound basis for eliminating this species from future consideration on seasonally dry, sloping lands.

5.4.3 Cattle herd management mathematical model

A cattle herd management mathematical model that maximises the net present value of the cattle operation per hectare (*NPVCP*) through the purchase and sale of cattle over time, subject to the annual available forage throughout the life of the investment, was developed with the Solver tool in Excel. The mathematical notation follows.

$$\text{Maximise } NPVCP = \sum_{t=0}^{T} \frac{\left((Sales_t - PCC_t - AM_t - F\&Y_t)/\sum_{f=1}^{F} HA_f\right) - \sum_{f=1}^{F} FEC_{ft}}{(1+r)^t} \quad (4)$$

where

$Sales_t = \sum_{c=1}^{C} Snum_{ct} \times SPrice_{ct} \times L_c$ (5)

$PCC_t = \sum_{c=1}^{C} Pnum_{ct} \times PPrice_{ct} \times L_c$ (6)

$AM_t = \sum_{c=1}^{C}(LH \times LC \times AE_c \times Herd_{ct}) + Cons$ (7)

$Herd_{ct} = Herd_{ct-1} + Pnum_{ct} - Snum_{ct} + CR_c \times Herd_{ct-1}$ (8)

Subject to constraints:

$AForage_t = \left(\sum_{f=1}^{F} DM_{ft} \times HA_f\right) + SForage_{t-1}$ (9)

$RForage_t = \left(\sum_{c=1}^{C} Herd_{ct} \times AE_c\right) \times FR$ (10)

$AForage_t = RForage_t + SForage_t$ (11)

$Snum_{ct} \geq 0$ (12)

$Pnum_{ct} \geq 0$ (13)

$SForage_t \geq 0$ (14)

Table 6 provides an overview of: (1) the decision variables solved by the model (Dec); (2) scalar parameters (SP) and vector and matrix parameters (P) that are requested from the model user; and (3) derived parameters (Der), which are a function of Dec, SP, and P. Index sets associated with variables and parameters in Table 6 are described in Table 7. The decision variables in the model are the number of cattle to purchase, $Pnum_{ct}$, and the number of cattle to sell, $Snum_{ct}$. Eqs. (5)-(8) are mathematical definitions of derived parameters introduced in Table 6.

Cattle are introduced to the systems when trees or leucaena are sufficiently established. For trees, this is generally when they reach a DBH of about 10 cm. Leucaena needs to have been established one year before introduction of cattle in year 2. On the basis of tree growth functions defined above, Table 8 summarises the year in which fences and cattle yards are constructed and cattle are introduced to the systems.

Table 6 Decision variables (Dec), derived parameters (Der), vector or matrix parameters (p), and scalar parameters (SP) for the mathematical model

Name	Variable or parameter	Description
$Snum_{ct}$	Dec	Number of cattle sold
$Pnum_{ct}$	Dec	Number of cattle purchased
$Sales_t$	Der	Sales revenues (F$)
PCC_t	Der	Purchase cost of cattle (F$)
AM_t	Der	Annual cattle management cost (F$)
$F\&Y_t$	P	Fencing and yarding cost installed (F$)
FEC_{ft}	P	Forage establishment cost (F$/ha)
HA_f	P	Hectares on the farm (ha)
r	SP	Real (net of inflation) discount rate (%)
$SPrice_{ct}$	P	Farmgate cattle sale price (F$/kg liveweight)
L_c	P	Liveweight (kg). Livestock are purchased at liveweight corresponding to the beginning of the year liveweight, and livestock are sold at liveweight corresponding to the end of the year liveweight (see Table 10)
$PPrice_{ct}$	P	Farmgate cattle purchase price (F$/kg liveweight)
LH	SP	Labour hours (hours/AE/y)
LC	SP	Wage paid to labour (F$/hour)
AE_c	P	Adult equivalents (see Table 10)
$Herd_{ct}$	P	Composition of the herd over time (numbers of animals)
$Cons$	SP	Annual consumables to manage the herd (F$)
CR_c	P	Calving rate. Zero for all cattle classes except cows (%)
$AForage_t$	Der	Available forage to feed all cattle in the herd (kg DM)
$RForage_t$	Der	Required forage to maintain the health of all cattle in the herd (kg DM)
$SForage_t$	Der	Surplus forage to requirements in a given year that is carried over to feed cattle in the following year (kg DM)
DM_{ft}	P	Dry matter production (kg DM/ha/y)
FR	SP	Annual feed requirement for healthy livestock (kg DM/AE/y)

Table 7 Index sets used in the herd management mathematical model

Name	Description
$t \in T$	Time since commencement of the system being modelled. Note that in many scenarios, cattle management does not commence until several years after investment in the system has started, because trees are being established.
$c \in C$	Classes of cattle are: bulls, cows, calves (<1 y.o.), steers (1-2 y.o.), heifers (1-2 y.o), steers (2-3 y.o.) and heifers (2-3 y.o.).
$f \in F$	Forage types are open tropical pasture, tropical pasture under vesi and pine, tropical pasture under teak, tropical pasture under pine, tropical pasture under spotted gum, sandalwood with leucaena, stylo and tropical pasture, and tropical pasture with leucaena.

Table 8 Year of fence and cattle yard constriction, and introduction of cattle by system

System	Year cattle introduced
Tropical pasture only	0
Leucaena improved tropical pasture	2
Vesi and pine silvopasture	5
Teak silvopasture	4
Pine silvopasture	4
Spotted gum silvopasture	4
Spotted gum with leucaena improved tropical pasture [1]	2
Sandalwood, stylo and leucaena silvopasture with electric fence	2
Sandalwood, stylo and leucaena silvopasture	10

Note: 1. Experience in Queensland spotted gum silvopastoral systems suggests that under cell grazing, where cattle are only resident in a cell for one week in every 10 weeks and have access to leucaena and open pasture, losses of spotted gum trees will be acceptably low before the trees reach 4 years. Therefore, cattle are introduced in year 2 when leucaena is sufficiently established.

Table 9 reports the calving rates, CR_c, assumed in this analysis. Calves grow to steers, heifers and cows over time as outlined in Figure 6 at rates of liveweight gain indicated in Table 10. Eq. (9) estimates the amount of forage available to the cattle, and eq. (10) estimates the amount of forage required to feed the cattle herd. Eq. (11) ensures the required forage does not exceed the available forage, and allows the carry-over of surplus forage to the next year of the optimisation. Appendix G details forage establishment costs (FEC_{ft}) and dry matter production (DM_{ft}) for tropical pasture, leucaena and stylo. Costs, revenues and feed requirements for the cattle herd management mathematical model are defined in Table 11.

Table 9 Proportion of cows successfully rearing calves to weening (calving rate, CR_c)

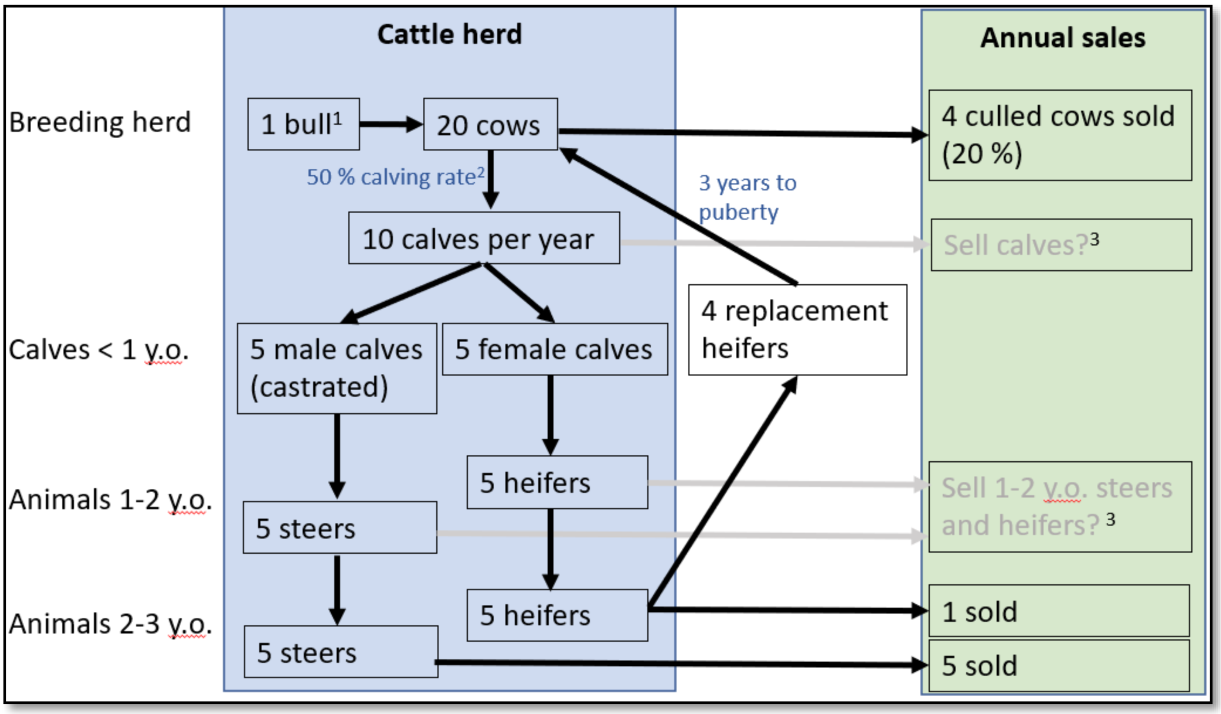
Herd management parameter	Modelled systems		
	(a) Tropical pasture only (b) Vesi, Teak, Pine and spotted gum silvopastoral systems	(a) Leucaena improved tropical pasture (b) Spotted gum and leucaena improved tropical pasture [3]	Sandalwood and leucaena systems [4]
Proportion of pregnant cows (%)	70	85	85
Calf mortality rate	10	5	5
Proportion of cows with calf after mortality (%) [1]	63	81	81
Calf gifting, strays and theft per 100 cows	13	13	3
Proportion of cows successfully rearing calves to weening, CR_c (%) [2]	50	68	78

Notes: 1. This is proportion of pregnant cows x (1 – calf mortality rate).
2. This is proportion of cows with calf after mortality – calf gifting, strays and theft.
3. Livestock in systems with leucaena have better body condition, resulting in improved pregnancy rates and lower calf mortality relative to the other systems.
4. The sandalwood systems with leucaena are on only 20 ha, which is assumed to improve herd management and reduce losses due to strays and theft.

Table 10 Adult equivalents and liveweight by cattle class

Cattle class	AE_c	Tropical pasture without leucaena			Leucaena at 40 % of diet		
		L_c begin year (kg)	Growth rate (kg/day)	L_c end year (kg)	L_c begin year (kg)	Growth rate (kg/day)	L_c end year (kg)
Bull	2	600	na	600	700	na	700
Cow	1.2	425	na	425	580	na	580
Calf	0.4	32.5	0.35	160	32.5	0.5	215
Steer (1-2 y)	0.5	160	0.35	288	215	0.5	398
Heifer (1-2y)	0.5	160	0.35	288	215	0.5	398
Steer (2-3y)	1	288	0.35	416	398	0.5	580
Heifer (2-3y)	1	288	0.35	416	398	0.5	580

Figure 6 Illustration of the herd structure by cattle class accommodated within the herd management mathematical model.



Notes: 1. The model retains a maximum bull to cow ratio of 1:30.
2. Considering rate of pregnancy, calf mortality, calf gifting and theft (Table 9).
3. These grey font sale options were available in the herd management mathematical model, but never adopted in the optimal solution for any scenario.

Source: Adapted from an unpublished herd structure model for cattle producers in Vanuatu with permission and advice from Associate Professor Scott Waldron, University of Queensland.

Table 11 Other parameters for the cattle herd management mathematical model

Parameter	Supplementary description	Level
r (%)		0.08
SPrice$_{ct}$ (F$/kg liveweight)	For livestock under two years	4.91
	For livestock over two years	4.50
PPrice$_{ct}$ (F$/kg liveweight) [1]	For livestock under two years	4.91
	For livestock over two years	4.50
F&Y (F$) [2]	30 to 40 AE on 20 ha with four x 5 ha grazing cells and electric fence around the sandalwood [3]	85,160
	30 to 40 AE on 20 ha with four x 5 ha grazing cells [4]	36,360
	150 AE on 200 ha with property perimeter fence only [5]	82,350
	250 AE on 200 ha with 10 x 20 ha grazing cells [6]	187,450
LH (hours/AE/y) [7]	These hours represent the time spent managing all aspects of the business, including calving, weening, mustering, castrating, fence repairs, marketing and sales.	28.6
LC (F$/h)		4.00
Cons (F$)		2000
FR (kg DM/AE/y)		3650

Notes: 1. In the absence of better information, it is assumed that livestock can be purchased for the farm at the farmgate liveweight sale prices.
2. Fencing and cattle yard cost estimates are the average of two online quotes from Australian suppliers, but substituting Fijian contract labour costs at F$6/h.
3. Only for the sandalwood with electric fence scenario, with 2286 m of two-strand electric fence per hectare running along the outside of each of the double rows of sandalwood.
4. Only for the sandalwood silvopastoral system without the electric fence.
5. All silvopastoral systems scenarios except sandalwood and spotted gum with leucaena improved tropical pasture.
6. Spotted gum with leucaena improved tropical pasture and leucaena improved tropical pasture scenarios.
7. The average herd size of second-tier cattle producers in Fiji is 70 AE (Cole *at al.* 2019), and it has been assumed that 1 FTE (2000 hours per year) is required in Fiji to manage 70 AE.

Liveweight farmgate cattle price justification

Cole *et al.* (2019) reported average farmgate prices in Fiji of F$2.25/kg liveweight in 2012, and that the best cattle in Fiji were fetching F$3.00/kg liveweight. Personal communication with a Fiji Ministry of Agriculture Livestock Extension Services Officer indicated that liveweight farmgate prices in 2022 were $5.50/kg and $6.00/kg for cattle at least two years old and under two-years, respectively. The 144 % price increase from F$2.25/kg to F$5.50/kg has been mirrored by 132 % increases in farmgate prices in Australia over the same time period (Meat and Livestock Australia Statistics Database: http://statistics.mla.com.au/Report/List). Nonetheless, the more conservative cattle prices reported in Table 10 have been adopted for base case analysis purposes. The sensitivity of LEV to cattle prices is examined (see Appendix H).

5.4.4 Sensitivity analyses

Sensitivity analyses can be performed on any variable in the tree crop and cattle production models. Sensitivity analyses have been included in Appendix H of this report for:

1. Minimum viable farm size;
2. sandalwood growth rate (0.2 cm/y to 0.7 cm/y) and stumpage prices;
3. timber stumpage prices (± 20 % and ±40 %);
4. tree growth rates for non-sandalwood silvopastoral systems (± 20 % and ±40 %);
5. farmgate liveweight cattle prices (± 20 % and ±40 %); and

6. the discount rate (4 % to 20 % in two percentage point increments).

5.5 Socio-economic impact of silvopastoral system adoption in Fiji

The potential economic impact of establishing silvopastoral systems in seasonally dry areas of Fiji on 30,000 ha of sloping, environmentally degraded land that has close to zero opportunity cost has been evaluated. It is unlikely to be technically or biophysically feasible to establish large areas of sandalwood in these landscapes. Given that a sterile leucaena variety is not yet commercially available, it may be prudent to be cautious about the widespread adoption of leucaena systems in Fiji. For illustrative purposes, the spotted gum silvopastoral system was been assessed to provide an example of the regional economic benefits of silvopastoral system adoption in Fiji.

The evaluation assumes there are 1000 ha in each spotted gum age class from one to 30 years. Thus, in any given year, 10 % of the landscape is not producing any cattle, since cattle are introduced to these systems at age 4. Also, during each year, 1000 ha of 30-year spotted gum would be clearfelled for sawlogs and large poles, and 1000 ha of 15-year spotted gum would receive a commercial thinning yielding low-value logs. Annual production of beef and timber per hectare in terms of volume and value by age class have been taken from the financial analyses described above. There were insufficient resources in this project for value chain analysis to project ‘upstream’ and ‘downstream’ flow on income benefits from increased regional farm income.

Direct livestock management employment has been estimated with the assumption that one FTE (1920 hours per annum) is generated per 70 AE, which is approximately the rate employment in commercial livestock operations in Fiji (Cole *et al.*, 2019).

Employment in forest management throughout the 30,000 ha of spotted gum silvopastoral systems was estimated on the basis that the modelled spotted gum management regime required 121 hours of labour per hectare over a 30-year rotation, excluding commercial harvesting (see Appendix F). Employment generated by the annual harvest and processing of spotted gum was estimated from the Fiji Ministry of Forestry (2021a) reported national formal employment rate of 0.605 FTEs in timber harvesting and sawmilling per 1000 m^3 of log harvested in 2018. There were insufficient resources in this project for value chain analysis to project ‘upstream’ flow on employment benefits from increased levels of tree establishment and management on farms.

The volume of carbon sequestered on site in the trees has been calculated starting with the merchantable volume per hectare estimates for all stand ages from this study. Based on Ximenes *et al.* (2004) finding that the merchantable bole accounts for 58.2 % of above ground biomass in merchantable spotted gum trees, total above ground biomass was determined. A standard below-ground biomass factor recommended for use by the Intergovernmental Panel on Climate Change suggests that below ground biomass is approximately 25 % of total above ground biomass (i.e. crown, bark, stump and merchantable bole). The basic density of spotted gum is 800 kg/m^3, and this was converted to carbon volume with recommended factors for sclerophyll forests in Australia: 50 % of the above ground biomass is carbon; and 48 % of below-ground biomass is carbon (Gifford, 2000b, a).

6 Achievements against activities and outputs/milestones

Changes to the administrative structure of the Fiji Ministry of Forestry in 2019, followed by travel restrictions due to Covid from early 2020 to early 2022, resulted in the budget being reduced by 70 %, and scope of the project being substantially reduced. The project was scaled back from 16 to eight research activities more appropriate for the necessary emphasis on desk-top analysis. Activity numbers have been retained from the original larger project, such that activity 3 (not 1) is the first activity under objectives 3 and 4.

Objective 1: To examine the barriers and constraints to sloping land agroforestry in Fiji, and identify gender-inclusive policy and institutional frameworks and instruments to overcome these and facilitate the establishment of silvopastoral systems

no.	activity	outputs/ milestones	completion date	comments
1.1	Examine the socio-cultural, environmental, institutional, market, trade and land tenure contexts of Fiji agroforestry, and identify policy, institutional and governance constraints limiting agroforestry adoption on Fiji sloping lands.	Report on policies, laws and governance settings for land-use management and agroforestry, identifying potential reforms (including accounting for gender and age) of policy, institutional and governance frameworks.	30 June 2022	Completed report in Appendix B

Objective 2: To identify potentially suitable combinations of pasture, livestock and tree species for silvopastoral systems on seasonally dry, sloping land areas on Viti Levu and Vanua Levu….

no.	activity	outputs/ milestones	completion date	comments
2.1	Design, test and document the methodology for a geospatial analysis to identify sloping land suitable and available for CLT agroforestry in Fiji.	A report which describes the necessary datasets, procedures, software, hardware, costs, required training and consequent expertise, opportunities for capacity building, usefulness and limitations of the analysis. The report will also provide a preliminary estimate of land area suitable for silvopastoral systems.	30 March 2022	Completed report in Appendix C
2.2	Develop tree species list and collect technical information on tree species performance	Write a report on the potential performance of tree species on sloping land	20 July 2022	Completed write-up in body and appendices of this report
2.3	Estimate livestock carrying capacity	A report summarising the technical feasibility, costs and potential production of pastures and livestock on seasonally dry sloping lands in Fiji.	3 July 2022	Completed write-up in body and appendices of this report.
2.4	Design sloping land silvopastoral systems	A report summarising the silvopastoral system designs.	3 July 2022	Completed write-up in body and appendices of this report

Objective 3: To collate production, cost and revenue data for individual tree and livestock species, and evaluate the financial performance (from a landholder perspective) of selected silvopastoral systems for alternative business models.…

no.	activity	outputs/ milestones	completion date	comments
3.3	Estimate per hectare financial returns for selected sloping land livestock and tree species	A suite of Excel-based discounted cash flow financial models for selected livestock and tree species.	3 July 2022	Excel financial models for silvopastoral systems are available from authors.
3.4	Estimate financial returns for silvopastoral systems, and suitability for adoption	Financial models for selected silvopastoral systems and a report detailing methods, results and recommendations arising from the financial modelling.	11 July 2022	Completed write-up in body and appendices of this report.

Objective 4: To develop and evaluate a regional-scale silvopastoral system adoption scenario …

no.	activity	outputs/ milestones	completion date	comments
4.3	Develop and evaluate regional-scale silvopastoral system adoption scenario	A report projecting regional economic benefits of adopting recommended silvopastoral systems	11 July 2022	Completed write-up in body and appendices of this report.

7 Key results and discussion

This section presents and discusses key results from the research activities. The reader is referred to the appendices for further details. Section 7.1 discusses policy and institutional settings, as well as barriers and opportunities for agroforestry in Fiji. Section 7.2 provides a preliminary estimate seasonally dry sloping land area suitable for silvopastoral system development on Viti Levu. The financial performance of silvopastoral systems from a leaseholder's perspective are reported in Section 7.3, and the economic benefits of a 30,000 ha silvopastoral industry are projected in Section 7.4. Section 7.5 summarises some of the greatest challenges to expansion of silvopastoral systems in Fiji.

7.1 Policy and Institutional settings, barriers and opportunities

7.1.1 Policy-relevant observations from the project planning trip in December 2018

The SWOT analysis during the project planning trip in December 2018 covered all aspects of CLT agroforestry systems (AFSs). Some were directly related to policy issues while others pointed towards policy change. The list of all strengths, weaknesses, opportunities and threats, and their point allocations is presented in Appendix B, with a more detailed summary of the highest ranked SWOTs provided in Table 12 (below). Together with the limited in-country activities undertaken, the following policy-oriented themes emerged from the SWOT analysis.

A. Policy Issues

- Agroforestry does have a clear 'home' in the Forest Policy, and it is relevant to three focus areas: Sustainable Forest Management; Plantation Development; and Product development (including value adding).
- Agroforestry is mentioned in the latest agricultural policy documents but there is still limited agroforestry in Fiji; this suggests the policy is not effective.
- There is no land use policy that designates where agricultural land ends and forest land begins.
- The main policy drivers dominating policy discourse at present are REDD+ and the IUCN red list.
- A log export ban has been in place for 10 years, which has reduced timber production and perhaps impacted the perception of the value of forestry and hence agroforestry.

B. There is low interest in Mataqali communities for tree planting

- Monetary gain is a much stronger motivation than conservation. This should be a positive for agroforestry, which can be about both.
- Communities have high expectations about benefits from forestry and agroforestry, but anticipate that this can be achieved with low effort and inputs.
- Landholders are generally not interested in agroforestry and have limited capacity. They are highly dependent on Ministry employees to manage plots, and on NGOs generally.
- There is lack of long-term land-use planning. People change their minds about what they want to do on replanted land and may kill the trees, usually with fire, to change land use.
- After planting, the Ministry of Forests remains engaged with the community for 2-3 years, but after the Ministry leaves, the communities lose interest.
- Problems and conflicts within communities makes the successful establishment of plantings or nurseries difficult.

- If communities get angry with the planting arrangements, or with each other, they burn the plantings.

C. **Planning issues**
- Plantations are often planted in inappropriate areas that are being used, or will be used, by local communities for other purposes, for example, cattle or medicinal plants. There was little recognition or understanding that these can be managed together and silvopastoral or agroforestry systems.
- Communities need incentives to plant trees. 'The Ministry' should provide incentives consistent with a village plan, e.g. distribute cash for scholarships for kids if that is what they want. Which Ministry has that role was not well articulated.

D. **Governance issues**
- Ministry of Forests only manages trees, not land, and there are many divisions with different roles.
- The Ministry of Agriculture has a broader extension program than the Ministry of Forests; both crop and livestock extension. One of their main extension objectives is poverty reduction.
- Programs often depend on donors and are not self-sustaining.
- When the Ministry of Forests visits a community, they don't talk trees. Trees enter the discussion as a way to support what the community really wants, e.g., electricity and water.
- Social relations, power and influence play an important role in some aspects, such as favourable or preferential access to land, special land lease rates and the level and management of risk (e.g. fire) and conflict.

E. **Gender**
- All villages are different, and a 'cookie-cutter' approach cannot be used.
- The social roles of men and women should be determined on the basis of the norms and values of the specific culture of the community.
- Proposed interventions must be culturally appropriate and the impacts of them on the existing roles of people (men, women and youth) must be understood.
- Men and women will have different preferences about crops, trees and animals.
- Youth may be particularly motivated by cash crops (such as kava).
- There needs to be a social acceptance of recommended species if agroforestry is to be successful.

F. **Value chains**
- The role of seed and cattle traders needs to be better understood.
- There are enough sawmills, but other areas of possible value chains are under-developed.

Table 12 SWOT Analysis results for Crop-Livestock-Tree (CLT) Systems

Strengths	Weaknesses
CLTs can be adapted to different types of landscapes through selection of appropriate and complimentary crops, animal and trees species. They produce multiple products in different time frames, giving more market choices. Combined, crops, trees and livestock generate cash crops and capital assets supporting immediate and long-term needs of farmers.	CLTs are more complex and can be more expensive to start and maintain. There is a high opportunity cost of business as usual (non-use). Farmers and other investors in CLT may need to borrow to finance their activities, however there is currently limited access to finance; such approaches may be seen as high risk by lending Institutions.
CLTs provide potential environmental co-benefits such as soil enrichment, protection of land, and increases to forest cover. Through their diversity in products and timeframes, CLTs may be more resilient, to natural disasters and climate change.	CLT is experimental and developmental in Fiji. While there is some experience, the results of new research can take a long time, to show the benefits, especially from tree growing. While agroforestry systems are familiar in Fiji, there is a lack of experience with CLT systems and extension services will be needed.
With limited high-quality arable land in Fiji, well designed CLT systems can better use the available less-productive land and potentially restore degraded land. It has the advantage of having few competing land uses. CLT has the advantage over other systems, of being a familiar land -use concept, making adoption of new technology easier.	Past agroforestry programs have occurred on medium to high productive land. Farmer expectations for CLT on degraded sloping lands may be unrealistic because these lands have lower fertility and will result in lower yields. There will be trade-offs between short term income from crops and livestock against longer term profits, e.g. from tree products.
CLT agroforestry can help achieve a number of national socio-economic development objectives, including increased local food production and availability of higher quality more nutritious food, with associated health benefits.	There is some processing capacity in Fiji, but industry development will be needed for new product value chains. Proximity to processors and the logistics, within Fiji and to export markets may pose some constraints. CLT and processing of products may require increases in available and skilled labour
Opportunities	**Threats**
CLTs can improve livelihoods and support rural development. They provide an opportunity to improve the productivity of underutilised land. CLTs support employment opportunities but can also potentially be labour saving.	Unclear and complex land tenure may increase the cost of CLT systems and result in community conflict if land use rights are not clearly established. Lack of awareness and community mindset may hinder CLT agroforestry uptake.
There is scope to design CLTs to deliver co-benefits with direct value to farmers such as PES for watershed protection and carbon sequestration and that also deliver broader benefits, such as improved quality of living conditions such as clean air, water quality, and visual amenity etc. They can also contribute to global targets and Fiji's international obligations.	If left unmanaged, CLT systems may be vulnerable to a number of risks associated with natural and human-induced fire, other natural disasters, unknown pests and diseases and climate change.

CLTs are an attractive development tool. They directly benefit farmers and have potential to grow local industry and partnerships between farmers and SMEs. They may generate support from donor partners and build confidence of the financial sector for lending programs.	New donor and political discourse supporting agroforestry, and the withdrawal of donor funding may impact already limited government budgets and resources to provide technical support and administration of CLT systems, excessive red-tape along products value chains, may limit the uptake and value gained.
Increased national wealth and GDP in the agriculture, forestry and processing sectors will increase departmental budgets which will in turn support improved development and implementation of policy and research/education in agroforestry in Fiji. Flow-on effects should see increased community interest in planting trees.	With new crops, especially long-term crops, there will be market uncertainty. Lack of processing capacity may inhibit value-addition in the short term. International markets standards and fiscal and non-fiscal trade barriers exist and will need to be addressed.

7.1.2 Institutional and policy settings that impede or support adoption of silvopastoral systems in Fiji

Fiji does not have a separate strategy, policy or law for agroforestry. There are policy-aspirations for the development and expansion of agroforestry generally as a land use in Fiji, oriented to different and sometimes converging goals. However, there are conceptual complexities that present barriers in realising these goals. These are not particularly unique to Fiji and we draw on van Noordwijk (2021) who noted that several artificial divides often hinder progress in relation to agroforestry:

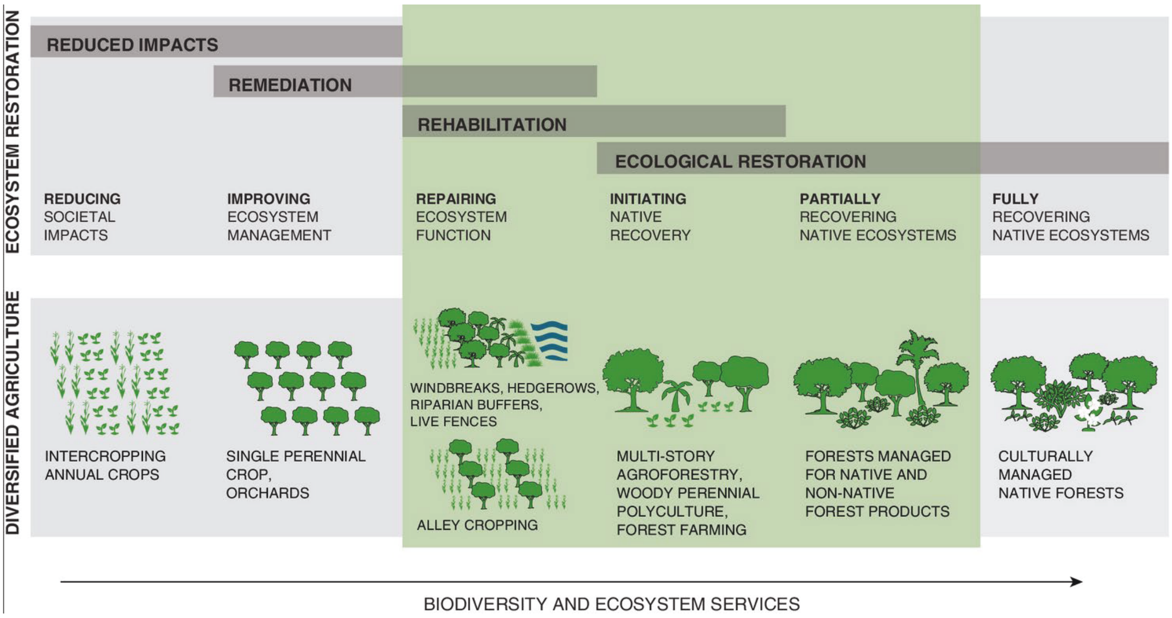
1. the segregation of "forestry trees" and "agricultural crops and livestock", ignoring the continuity in functional properties and functions of these often spatially aligned systems;
2. the identification of agriculture with provisioning services and the assumed monopoly of forests on other ecosystem services in the landscape, challenged by the opportunity of "integrated" solutions at landscape scale;
3. gaps in local knowledge of farmers/agroforesters as landscape managers;
4. recognition of the contributions of social and ecological sciences; and
5. the path-dependency of forestry, environmental or agricultural institutions, and emerging policy responses to "issue attention cycles" in the public debate, such as, green-growth, climate change and reforestation.

In our analysis of the policy settings for agroforestry in Fiji, it is clear that there is a segregation (although not absolute) between trees, crops and livestock, and that this impinges on progress for developing a policy or strategy for agroforestry, and the advance of agroforestry technology.

In climate policies, for example, agroforestry is viewed primarily as an adaptation measure for progressing climate resilience through 'climate smart agriculture'. However, the perceived roles of agroforestry as a mitigation measure, e.g. through carbon sequestration in trees, are less well articulated. Indeed, the definition of forests in Fiji's Climate Change Act 2021 excludes tree stands in agricultural production systems. In agricultural policy, agroforestry is seen as a more sustainable form of agriculture, as well as 'climate smart'. However, agroforestry is not actively promoted as a commercial land use system in agricultural policy. Forestry strategy generally includes agroforestry, but with a firm emphasis on trees and their products.

The presentation and determinants of the physical nature of what an agroforestry system is made of, and what it looks like, can also be disparate – sometimes resembling natural forest systems (complex/diverse) or alternatively being structurally very simple (e.g. trees plus crops; trees plus livestock). When described in the context of landscape restoration or being compatible with conservation policy goals, preference may lean towards the former, but in the case of better use of degraded land, simpler systems dominate. A continuum developed by Hasting et al. (2020), and reproduced in Figure 7, depicts this well.

Figure 7 Conceptual diagram highlighting the intersection between ecosystem restoration and diversified agriculture



This project- which is looking specifically at silvopastoral agroforestry as a land use option on degraded sloping lands, sits to the left-centre of Figure 7, depending on the number of tree species planted – Ministry of Agriculture (MoA) sees the livestock, Ministry of Forestry (MoF) sees the trees, Ministry of Environment (MoE) sees the climate benefits (resilience, avoided degradation/restoration and potentially GHG mitigation), Ministry of Trade (MoT) sees the products and Ministry of Health (MoH) sees the food/health benefits. Only MoF specifically aspires to develop an agroforestry strategy and, in its currently operational plan, this is not funded.

Despite this there maybe common spaces and institutional structures that are well suited to mediate the development of an agroforestry strategy for Fiji. Existing laws, policies, strategies and operational plans provide (in some cases require) spaces for Ministries to work together, but getting agroforestry on the agenda needs policy-makers to prioritise it.

Agroforestry is viewed as an 'inclusive' land use option – particularly for women and youth. However, what 'agroforestry' actually looks like in this context is not well described. Is it a 'traditional' land use allowing access to culturally important and subsistence-oriented products (sometimes conceptually oriented towards the participation of women; a gender bias), a commercially-oriented production system (oriented towards youth; a generation bias) or a hybrid approach that can provide for both? These differences are exacerbated because agroforestry is also institutionally dispersed – it can be found explicitly in the Ministry of Agriculture, Ministry of Forestry and Ministry of Economy, and implicitly in the Ministry of Trade and Ministry of Health, but structurally, the responsibly remains somewhat obscure.

Is (sloping land) agroforestry included and promoted in government strategies and plans for land use or is it omitted or excluded?

The Forestry Strategy 2007, the draft Plantation Policy, the proposed Agroforestry Strategy, programs for reforestation (mass tree planting) to address degradation, and references to

'Climate smart agriculture (Agroforestry)' all indicate that agroforestry is part of Fiji's future land use options.

The roles and promotion of crops and livestock are clear in Agriculture policy, and indications are that combined systems of trees, animals and crops are on the mind of policy makers. However, the actual processes to increase agroforestry as a land use have not progressed, in part because the concept is underdeveloped. Generally, it seems used as a generic term, often with an assumption that it is a 'traditional' or 'non-commercial' practice. Perhaps because of this, its priority is low in the context of Fiji's socio-economic development plans or policy priorities.

Where progress has been made, this has occurred with donor support. There is little spontaneous uptake, which indicates policies are not clear or sufficiently detailed, they have not been well communicated, or other factors are at play.

It appears that, although agroforestry is acknowledged as a 'climate smart' production system, the climate change policies may include some exclusions regarding tree stands in agricultural production systems. It is not clear how and whether agroforestry systems can participate in opportunities associated with carbon abatement projects domestically or internationally. This requires further clarification.

Are there institutional settings that enable or act as barriers to (sloping land) agroforestry?

There are various institutional structures in which agroforestry is explicitly embedded or to which is it well aligned. However, these do not appear to be working in favour of progressing agroforestry as a land use practice.

The Forest Act, for example, requires that the Forestry Board includes, amongst other members, at least one representative from each of the department of agriculture, the iTaukei Land Trust Board and the department of environment, thus bringing together four of the key ministries involved in agroforestry – environment, land, agriculture and forestry. This provides a high-level forum at which agroforestry could be discussed. MoF also has, in its structure, some institutional capacity aimed at afforestation, reforestation and agroforestry and, while the actual level of human resources and financial budget allocation for this to progress either the Draft Plantation policy or Agroforestry Strategy are not apparent, it could act as secretariate to the board for the development of this and as a focal point for inter-ministerial technical consultation.[4] This could fit with MoA's SDP which aims to provide space for collaboration including with other organisations and Ministries and with the strong statement by representatives from MoA at the United Nations Food Systems summit, which recognised the need to identify linkages and break silos and "to relook at government policies to support transformation".

Within the Ministry of Economy, the Climate Change and International Cooperation Division (CCICD) has a coordinating role and relationships with other cross-government/ministerial policies, and certainly climate change policy and associated mechanisms seem central to the contemporary and most-pressing policy issues in Fiji. The NAP process provides the opportunity to examine the interactions between all economic sectors in a coordinated and coherent way and seeks horizontal integration, with "National level mainstreaming by Ministries and Entities" needed to support mobilization and efficient use of resources. Agriculture is a focus and the actions proposed in the NAP through climate-smart agriculture, new agricultural technologies and practices, promoting coordinated multi-stakeholder collaboration regarding the generation of evidence, enhancement of local institutions, utilisation of both scientific and traditional knowledge, as well as an improvement in the coherence between climate and agricultural policies and finance (Lipper et al., 2014, in NAP

[4] *Noting we did not have access to lower-level budget details.*

2018). The role of forests is more focussed on REDD and the place of trees on agricultural land in the Climate Change Act remains somewhat unclear. However, the Emissions Reduction Purchase Agreement, and the financial incentives this brings, provide some indication that better inter-ministerial collaboration is needed for the commitments associated with this agreement to be achieved.

Structures set up to administer climate change initiatives generally seem to provide an opportunity under which a multi-sectoral group to progress agroforestry could be established.

What policy and institutional changes are needed to accelerate agroforestry policy?

There are other factors inhibiting the development of supportive policy and the adoption of agroforestry generally, and sloping land agroforestry in particular, and there are others that can provide an opportunity to elevate it as a policy priority. Key to both is aligning agroforestry with other strategic goals or programs. What is evident from the analysis is that climate change is currently at the heart of policy and is already driving change and presents a good opportunity for policy alignment and elevation.

The NCCS notes a sustainable forestry sector remains a key priority for Fiji's national climate change response, because by reducing unsustainable practices, there will be a range of co-benefits in relation to carbon mitigation, biodiversity conservation, ecosystem service protection, livelihoods protection, adaptation capacity, food security, as well as reduced risks of hazard events such as flooding and landslides. It includes:

- Climate Smart Agriculture: expanding agroforestry practices (e.g. plant shade trees and live fences for grazing of cattle or pigs under tree crops); and
- Sustainable soil and land management techniques – integrated crop-livestock farming and agroforestry into farm practices.

In the Low Emission Development Strategy 2018-2050, land availability is seen as key to enabling the contributions of forestry and agriculture to reducing emissions. The expansion of agricultural and forestry production areas can only take place in accordance with traditional land use rights in Fiji.

Fiji's emission reductions program will address the main drivers of deforestation and forest degradation through integrated land use planning, native forest conservation, and sustainable pine and mahogany plantations. Other aspects will focus on community-driven afforestation, climate-smart agroforestry, and alternative livelihoods initiatives.

- With respect to the draft Plantation Forest Policy, this is slated to include carbon forests, community forests, small-scale tree planting schemes, agroforestry (including food forests), urban forestry and private woodlots. It also recognises the 'need for a clear and coherent national policy framework to guide strategic actions and investments in these planted forests to reposition forestry as a desirable and sustainable land use'. This suggests these settings are not in place in Fiji now.
- The Reforestation of Degraded Forest (RDF) project is also working with communities to establish their own plantation forests. The 30MT15Y tree planting initiative supports the RDF activities through the planting of trees in other areas. This is strongly linked to climate change, green economy and COVID-19 recovery (thus inferring some socio-economic benefit). Agroforestry projects are taking place under 30MT15Y. Permanent Secretary for Forestry, Pene Baleinabuli said

> "Agroforestry bridges the gap that often separates agriculture and forestry by building integrated systems that address both environment and socio-economic objectives. Agroforestry can also improve the resiliency of agriculture systems and mitigate the impacts of Climate Change".

- The MoA SDP aims include strengthening the transition of smallholder farmers to commercial level. Agroforestry, as mentioned under Strategic Priority 3 “Climate Smart Agriculture”. This states “there will be support for sustainable land management, better soil management, integration of traditional and modern farming practices, water-use efficiency and agroforestry”. This links to goals for climate change, food production, and establishing partnerships. The MoA SDP is strong on crops and livestock, but relatively quiet on agroforestry.
- Speeches made at the UN Food Systems Summit 2021 by the Minister for Agriculture, Waterways and Environment used the strongest language in support of agroforestry approaches to land uses, oriented around the pressing topics of food security, but also drawing on associated issues related to health, climate change and environment. Concepts of polyculture, nature positive food systems, diversification, organic food, forestry or agroforestry systems, and food forests were all put forward, as were:
  - Promotion of regenerative agriculture, and support to communities to plant a diversity of trees, crops and integrating livestock activities in degraded areas to complement reforestation and sustain ecosystem services.
  - Achieving sustainable multiple trees and/or cropping systems, based on local traditional plant biodiversity and market’s demands to promote high-value ecosystems that are beneficial for people and the environment.

Policy and governance were seen as key to transformation.

Newer concepts of ‘green growth, a ‘green-economy’, and ‘green infrastructure’ all hinge on building a bridge between sectors to find land uses that enable production, but that mitigate natural disasters, address land degradation and reduce emissions.

COVID-19 exposed the vulnerability of economies and production systems, but approaches such as One Health also point to agroforestry solutions being conceptually well-positioned to examine interconnections among human and forest and ecosystem health. In response to COVID-19 sectoral ministries have shown that they can come together to address pressing issues and find solutions. During COVID-19 people went “Back to the Farm”, and readopted or adopted land use practices for both subsistence and development needs. Multi-product, multi-scale, multi-temporal systems are suited to resilient and climate smart approaches because (depending on the elements) they can provide immediate food needs, cash income from intermediate agricultural products as well as longer term security from trees providing products for domestic and export markets. These are likely to be more resilient to shocks, such as was experienced with COVID-19. Such systems are also inclusive: they can be intergenerational production systems with element attractive to men women and youth.

Due consideration is needed of what and how people want to participate in agroforestry and whether adverse consequences could arise. Cash crops can have good and bad social, economic and environmental outcomes. Land use conflict can arise, as has been seen with poorly planned plantations. The diversity of agroforestry elements necessitates good systems design - one model will not suit all.

Recent successes and lessons learnt elsewhere in developing agroforestry policies and strategies, such as in Africa, can point the way, but policy processes will need to change.

Leadership and drive of departmental heads is critical in getting a policy issue on the government’s agenda and moving it forward, but current top-down policy processes through which issues are progressed may need to accommodate greater community involvement in order to ensure adoption and sustainability. Lack of consolidated community support will affect policy support and implementation. While it is relatively easy to write policies by drawing inputs from internal and external advisors and experts, understanding the experiences of those whose practices the policies are trying to change is essential for effective adoption.

7.2 Preliminary estimate of seasonally dry sloping land area suitable for silvopastoral systems on Viti Levu

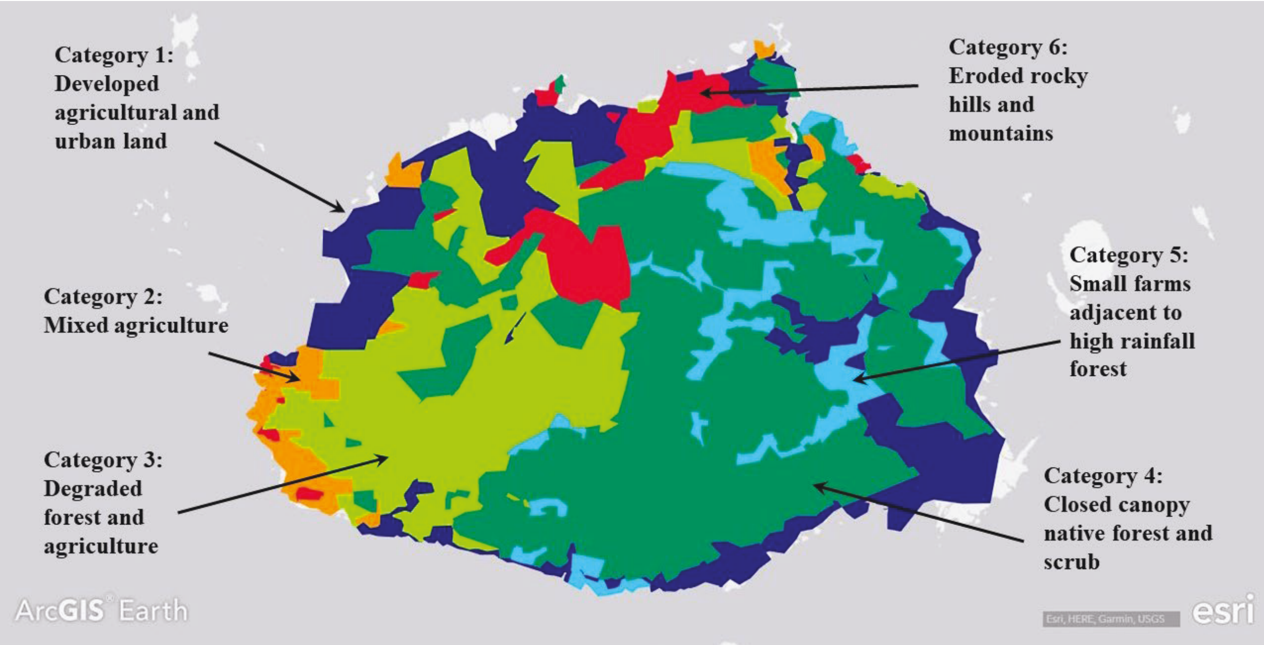
From the preliminary geospatial analysis, Viti Levu was classified into six dominant land use classes revealed in Table 13 and Figure 8, with the aim of revealing where establishment of silvopastoral systems may be desirable and possible in the future. Land in Category 1, including land devoted to sugar cane adjacent to Lautoka and Nadi in the north west, as well as intensive agriculture surrounding Suva in the south east, is too valuable under other land uses to be managed as silvopastoral systems, but small plantings at the boundaries of alternative dominant land uses may be feasible. Likewise, other land uses, including high value horticulture, will provide much greater benefits to society than silvopastoral systems on the small farms adjacent to cut over and partially cleared high rainfall native forest (Category 5).

Table 13 Area of six dominant land uses in Viti Levu to aid identification of areas suitable for silvopastoral systems

Dominant land use	Area (ha)	Percent of total landmass
1. Developed agricultural land (e.g. sugar cane) and coastal urban areas	175,000	17
2. Mixed agriculture on small farms	34,000	3
3. Degraded and partially cleared forest/scrub with some agriculture	229,000	22
4. Closed canopy native forest	486,000	48
5. Small farms adjacent to cut over and partially cleared high rainfall native forest	54,000	5
6. Eroded rocky hills and mountains	61,000	6
Total	**1,039,000**	**100**

Figure 9 is illustrative of the concentration of smallholder farms located in the south west of Viti Levu, which accounts for the majority of land in Category 2. This land appears to be highly suited to silvopastoral systems, although they would need to be appropriately scaled to the landholding size, and consideration must be given to the opportunity cost of land use change. Farmers often have unused portions of their land (steep or poor access) which they may be willing to devote to a long-term, low maintenance crop. However, the total area likely to become available for silvopastoral systems in this landscape is small.

Figure 8 Map of dominant land uses in Viti Levu to aid identification of areas suitable for silvopastoral systems



Note: Areas for these categories are reported in Table 13.

Figure 9 Small farms adjacent to the town of Kabisi in the south west corner of Viti Levu are illustrative of dominant land use category 2: mixed agriculture on small farms.

Degraded and partially cleared forest or scrub with some agriculture (Category 3) is the dominant land use in the seasonally dry half of Viti Levu. The opportunity cost of land use change in these areas is much lower than for Category 1, 2 and 5 lands. Figure 10 is illustrative of Category 3 in the central west of the island, and is also illustrative of Pastor Jacob's 500 ha leaseholding that provided inspiration for the development of silvopastoral system scenarios. Further north and closer to the coast, there are large areas of sloping grasslands in Category 3, for which Figure 1 better illustrates the landscape.

Figure 10 Extensive clearing on ridge tops and regrowth or residual forest in gullies, which is illustrative of Category 3 in the central west of Viti Levu

Native forest (Category 4) dominates the south-eastern half of the island, and it is not considered ecologically appropriate or socio-economically efficient to convert these lands into silvopastoral systems. The very low site quality of the eroded rocky hills and mountains of Category 6 is unlikely to support commercially viable agribusinesses (Figure 11).

Figure 11 Seasonally dry landscape adjacent to the town of Nadelei on Viti Levu, showing steep eroded hill tops with a thin strip of vegetation in the gullies, which is illustrative of Category 6

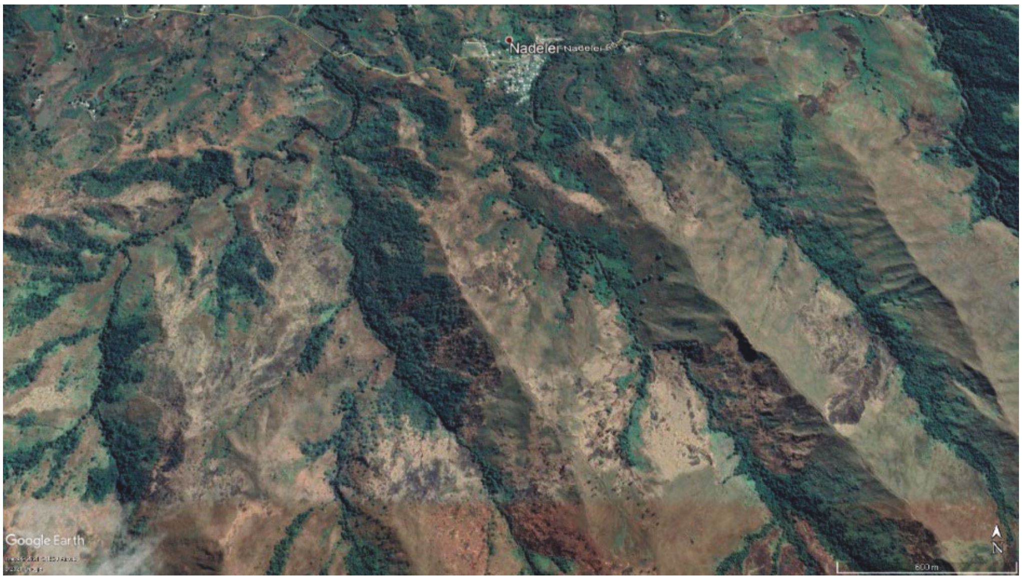


Table 14 classifies the dominant land use categories according to their suitability for silvopastoral systems, which helps to provide an indication of the land which may be best targeted in an expanded investigation in a future project. Silvopastoral systems are certainly suited to Category 1, 2 and 5 lands; however, because of high opportunity costs of land use change, limited adoption could be expected here. On the other hand, silvopastoral systems are potentially the highest and best productive use of Category 3 lands. and there appears to be potential to establish the larger lease holdings that are likely to be necessary to support stand-alone financially viable agribusinesses. According to Table 13, there are approximately 229,000 ha of this dominant land use type on Viti Levu, which is separate to and greater in area than the 194,768 ha of agricultural land in the nation (FAO and Fiji Ministry of Agriculture, 2021). There are also large areas of this land use type on Vanua Levu, which has not been accounted for in this preliminary assessment. Even if only a fraction of these lands were developed on Viti Levu as silvopastoral systems, this could generate large economic benefits for Fiji through increased livestock and timber production.

Table 14 Classification of dominant land use categories in Viti Levu according to six criteria which determine their suitability for silvopastoral systems

Criterion	Dominant land use					
	Category 1: Developed agricultural and urban land	Category 2: Mixed agriculture	Category 3: Degraded forest and agriculture	Category 4: Closed canopy native forest and scrub	Category 5: Small farms adjacent to high rainfall native forest	Category 6: Eroded rocky hills and mountains
1. Rainfall	High rainfall (south and east) or irrigated or seasonally low, but sufficient for seasonal crop (west and north)s	Sufficient for seasonal crops	Seasonally low	High	High	Seasonally low
2. Site quality	Very high	High to low	Variable, often low	High	High	Very low
3. Fire incidence	Protected	Variable	Frequent	Negligible	Low	Unknown
4. Terrain slope	Predominantly flat	Variable – steep terrain is not usually cropped	High variation over small areas	Steep and variable	Steep and variable	Steep
5. Road access	High	High	Often poor as distance from nodes extends	Poor to non-existent	Poor to non-existent	Poor
6. Proximity to processors	High, at Lautoka and Nadi	High, south of Nadi	Low	N/A	N/A	N/A
Overall suitability for silvopastoral systems	**Highly suitable on sloping land adjacent to developed agriculture, if protected from fire**	**Suitable for small areas of unused land on individual farms, if protected from fire**	**Suitable if protected from fire**	**Unsuitable (remnant forests)**	**Unsuitable (higher value horticulture opportunities)**	**Unsuitable (very low site quality)**

The preliminary dominant land use mapping performed for this analysis provides objective evidence of land use and revealed a large area potentially suitable for silvopastoral systems. However, a widened investigation is necessary. A limitation of this report is the absence of qualitative input from Fiji nationals. This means that those factors which are well understood by them – are absent here. This information may relate to social aspects such as the capacity of mataqali members to undertake collective action, the power relationships and social organisation and interaction of government agencies and mataqalis. For example, any discussion of agroforestry requires consideration of land tenure for long-term crops (i.e. trees). Fire control is necessary for agroforestry, particularly during establishment, and this requires broad community support and compliance. Hence any discussion must widen to include the social forces at play on any proposed site. It is proposed that the next steps of any expanded investigation should be carried out by officers of the Fiji government. GIS training to produce a current land use map will be an important first step.

The spatial analysis presented here, may begin to answer questions about current land use. However, the aim of ongoing research should be to support decision-making about what land use is desirable and possible in the future. GIS can help to answer these questions, but datasets of roads, mataqali boundaries and other cadastral data will be required. Agricultural cooperatives may be able to provide information about their members (e.g. addresses) which may allow targeted agroforestry extension assistance. Hence a further recommendation of this report is to include as wide a range of stakeholders as feasible in an expanded investigation. From a GIS modelling perspective, this would improve the quality of attribute data in spatial databases. For example, sawmills will have maximum haul distances over which they are prepared to source logs. Including these factors will ensure the validity of spatial modelling. For any proposed policy changes, including a wide range of stakeholders is simply a matter of practical politics.

Finally, GIS is a useful tool for thematic mapping and modelling, but it can provide questionable results. Rather than modelling areas of land, it may be better to ascertain the number of sites (e.g. farms) and the clientele who may be motivated to engage in agroforestry. From a wood processors perspective, aggregating log purchases from large numbers of adjacent woodlots may be financially feasible whereas widely scattered woodlots may not. Hence, the final recommendation is that an expanded investigation should link spatial data to as much attribute data (e.g. sites, haulage distance, roading) as possible. The database may then become highly attractive to other government agencies.

7.3 Financial performance of silvopastoral systems

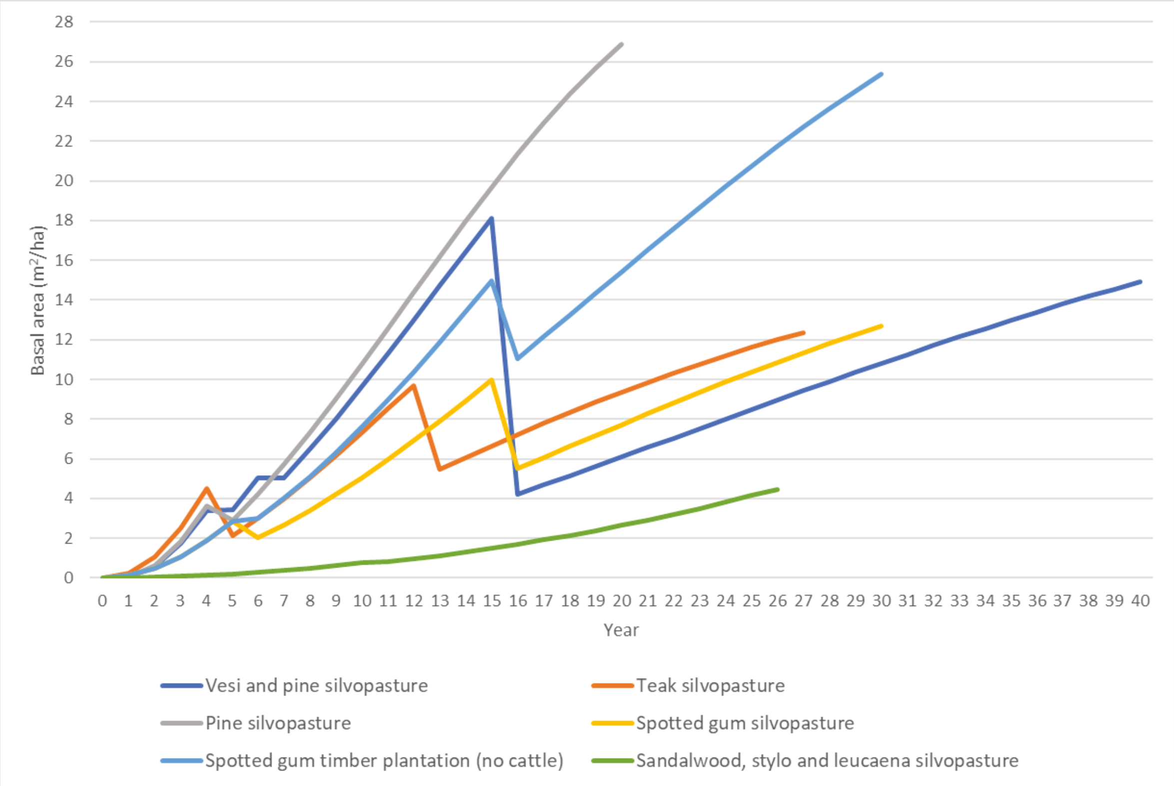
Estimated tree basal area over time for each silvopastoral system is illustrated in Figure 11. The spotted gum with leucaena improved tropical pasture system has not been plotted separately because tree growth on that fraction of the property growing spotted gum is identical to tree growth in the spotted gum silvopasture scenario. Sandalwood growth is the same with and without the electric fence, so only one sandalwood system is illustrated in Figure 12.

Figure 13 illustrates projected dry matter production for each silvopastoral system as a function of basal area. There are two livestock only systems (i.e. not silvopastoral systems) plotted in Figure 13; tropical pasture only and leucaena improved tropical pasture. Due to there being no competition from trees, expected annual production is constant. The leucaena improved tropical pasture system is considerably more productive than tropical pasture only. The remaining systems in Figure 13 are all silvopastoral.

Dry matter production in all silvopastoral systems with large trees is substantially impacted by competition over time. Temporary increases in dry matter production occurs when trees are thinned. The spotted gum with leucaena improved tropical pasture system was projected to be the silvopastoral system least impacted by tree growth. This was because trees and pasture cover 60 % of the 200 ha case study property, with leucaena and pasture growing on the remaining 40 % of the property. All other silvopastoral systems had trees on 100 % of the case study property, and the pine silvopasture system had the greatest negative effect on dry matter production because of the high retained stocking of trees. The vesi and pine silvopastoral system experienced a large increase in dry matter production at year 15 with the commercial harvest of all remaining pine.

Only the two sandalwood systems are projected to have greater dry matter production per hectare than the leucaena improved tropical pasture system. This is because all hectares in the system have leucaena[5], as well as the forage provided by the stylo intermediate host for sandalwood, which is more productive than the tropical pasture it replaces. Dry matter production available to cattle in the sandalwood system with an electric fence increases in year 10 when the electric fence is removed and livestock may graze the stylo between the sandalwood rows. From year 10, the sandalwood with electric fence scenario follows the same dry matter production path as the sandalwood scenario without the electric fence. The annual decline in dry matter production in sandalwood systems is slow because sandalwood is a relatively small tree with low competition impacts on tropical pasture and stylo production.

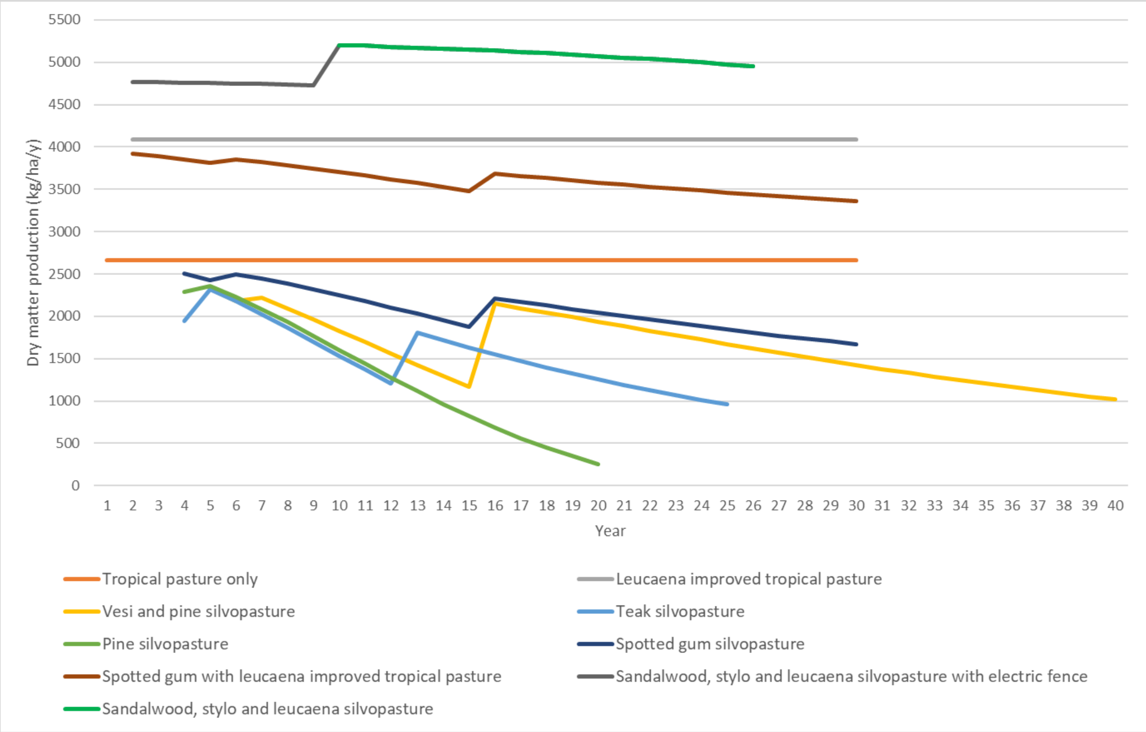
Figure 12 Basal area per hectare throughout the rotation of each silvopastoral system



Declining dry matter production over time in Figure 13 is reflected in declining herd size projected by the cattle herd management mathematical model over time in Figure 14. Note that the sandalwood systems are only 20 ha, while all other systems are 200 ha. *NPVCP* of the enterprise included total livestock value at the end of the simulated management period, and in more productive leucaena systems, *NPVCP* was maximised by a sell-off of cattle around years 23 to 27, followed by a build-up of livestock at the end of the simulation. The model can be modified to avoid this. All of the silvopastoral system scenarios without leucaena or sandalwood achieved an average herd size over the tree crop rotation of between 70 and 110 AEs, which is in the 'ball park' of existing commercially viable scales of cattle production in Fiji (Cole *et al.*, 2019).

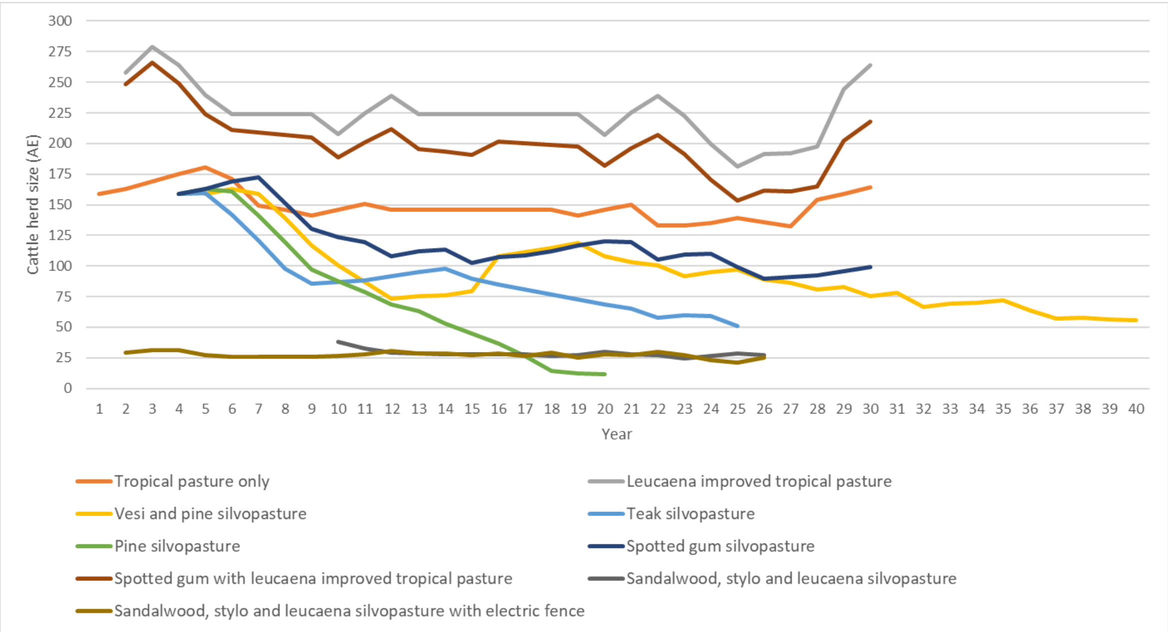
[5] *In the leucaena improved tropical pasture system and the spotted gum and leucaena improved tropical pasture silvopasture, sufficient leucaena was planted to achieve a minimum of 40 % of the cattle diet each year being leucaena. In both systems, this resulted in 40 % of the landscape or 80 ha in a 200 ha cell grazing system, being planted to leucaena.*

Figure 13 Dry matter production (kg/ha/y) from tropical pasture, leucaena and stylo for the years cattle are grazing in each silvopastoral system.



Notes: All systems have tropical pasture. Only systems described with leucaena and stylo in the figure legend have these forage components.

Figure 14 Optimal cattle herd size for the simulated systems



Annual net cash flows per hectare projected by the cattle herd management mathematical model are indicated in Figure 15. The negative net cash flows early are to purchase livestock, fencing and cattle yards. The rising value in the final year of each scenario includes the value of the unsold livestock. The y-axis has been truncated to focus on the annual cash flows.

Merchantable wood volume estimated for each system is illustrated in Figure 16. Merchantable volume for vesi, pine and spotted gum has been estimated under bark. Merchantable volume for teak has been estimated as heartwood volume, because sapwood substantially devalues teak logs. Sandalwood is reported in kilograms of heartwood per hectare on the secondary y-axis. Table 15 reports the mean annual increment (MAI) at clearfall harvest age for each species and total (undiscounted) harvest revenues throughout the rotation. The MAI for sandalwood is reported in kilograms. Teak and spotted gum plantations generated income from a commercial thinning at age 12 and 15, respectively, prior to the clearfall harvest. Those revenues are included in Table 15.

Figure 15 Net annual cash flows per hectare associated with livestock production

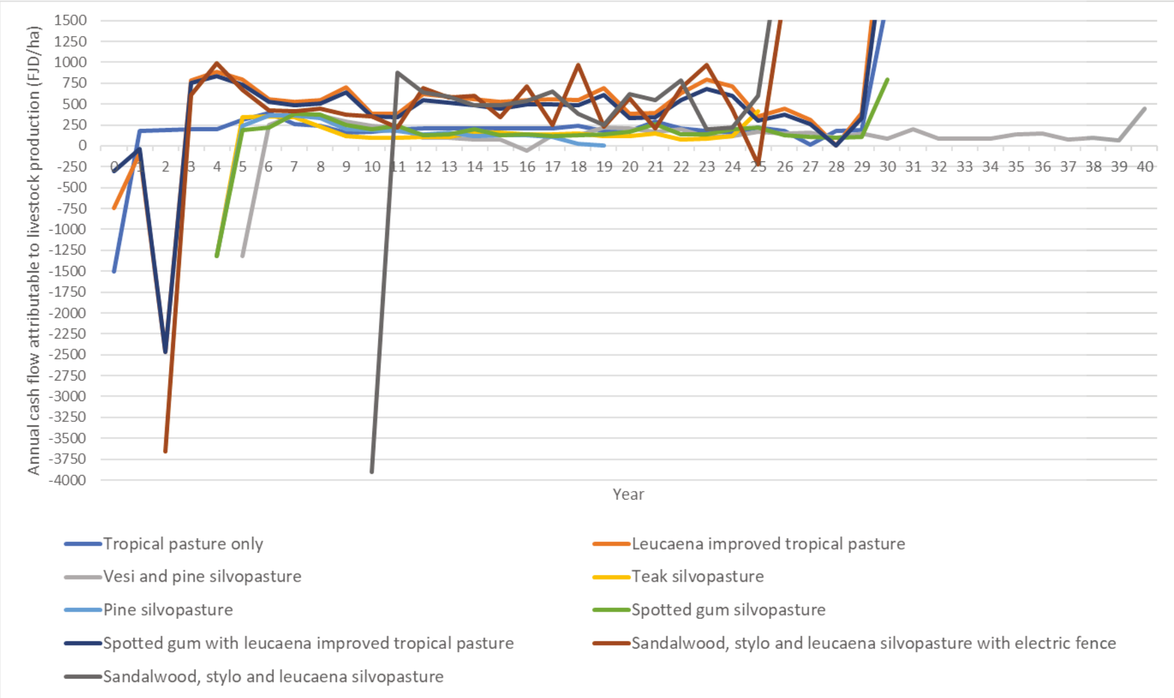


Figure 16 Merchantable wood volume (m³/ha or kg heartwood/ha) for each silvopastoral system

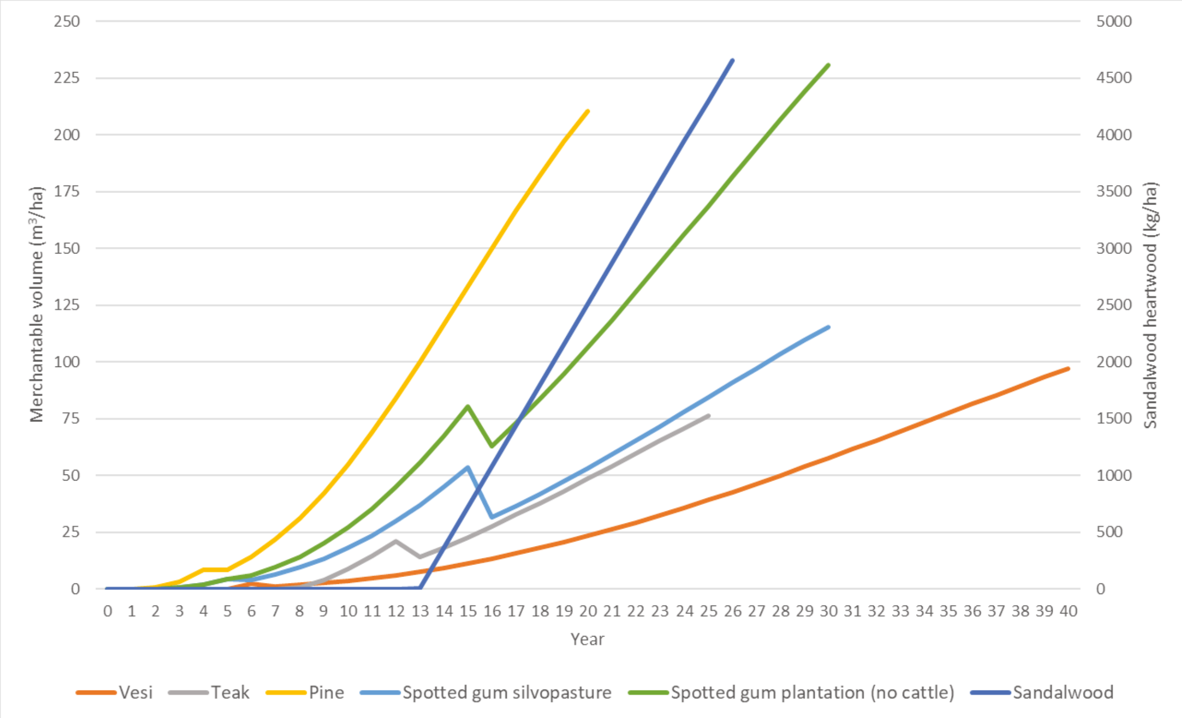


Table 15 Mean annual increment and timber harvest value for each system

Silvopastoral system	Harvest age (y)	Final stocking (stems/ha)	MAI (m^3/ha/y or kg heartwood/ha/y for sandalwood)	Harvest value (undiscounted F$/ha)
Vesi and	40	100	2.4	24,300
Pine	15	182	6.5	4,800
Teak	25	100	3.5	20,900
Pine	20	250	10.5	10,500
Spotted gum silvopasture	30	100	4.7	18,600
Spotted gum plantation (no cattle)	30	200	8.6	36,000
Sandalwood	26	172	178.9	329,970

Figure 17 reports the present value of all investment costs per hectare associated with each modelled system at an 8 % real discount rate (the bars in the figure). The tropical pasture only and spotted gum plantation (no cattle) scenarios have the lowest investment costs. This is because the former had no tree establishment and management costs, while the latter had no costs associated with cattle (e.g. livestock purchase, fences and yards). The sandalwood scenarios have the highest investment costs per hectare because of the need to manage intermediate and long-term sandalwood hosts, as well as the smaller scale of the operation (20 ha) increasing the costs of fencing and cattle yards on a per hectare basis. Figure 17 also reveals the proportion of the present value of these investment costs paid back to the investor by year 15 (the line plot). The livestock only systems performed best in this regard, more than fully repaying the investor by year 15. The spotted gum timber plantation (no cattle) and the two sandalwood scenarios are the two worst performing scenarios in terms of proportion of the investment paid back by year 15. This is explained by the former having no annual income from cattle and the sandalwood investments having high initial investment costs, which was exacerbated in the system without electric fences because the introduction of cattle had to be delayed until year 10.

Figure 18 Land expectation value of modelled systemsreports the land expectation value (*LEV*) of each modelled system at an 8 % real discount rate. The LEV indicates the present value per hectare that could be spent on other expenses not explicitly accounted for in this analysis, while still making at least an 8 % return on investment. The three main items the analysis did not account for were water provision, farm vehicles and work animals (e.g. horses). Given data limitations, the reader is cautioned against emphasising the absolute differences in LEVs between silvopastoral systems, and is instead advised to focus on the relative performance of the alternative systems. The relative performances will be much more robust to changes in model parameter estimates as improved data becomes available with future research.

The two sandalwood systems out-performed all others by an order of magnitude, and the y-axis in Figure 18 has been truncated to better highlight the potential returns to the other systems. The sandalwood system with an electric fence did not perform as well as the system without the electric fence because the increase in returns from livestock (animals can be introduced in year 2 instead of year 10) did not cover the increase in fencing costs. Despite the lower LEV, the electric fence system does provide the benefit of an annual income in the early years and faster investment payback (Figure 17), as well as reduced wildfire risk from reduced fuels, which has not been captured in this preliminary assessment. Cautionary comments about sandalwood systems are made in Section 7.3.1.

The third and fourth-best performing systems are projected to be the spotted gum with leucaena improved tropical pasture, and the leucaena improved tropical pasture, respectively. The spotted gum-leucaena system was 60 % planted to spotted gum silvopasture, and 40 % planted to leucaena improved tropical pasture. This produced less forage and cattle than the leucaena improved tropical pasture system. However, this was more than made up by the returns to timber.

The spotted gum timber plantation (no cattle) was the fifth-best performing system due to relatively low investment costs and high timber yield. However, this system generated no annual cash flows from cattle and had only repaid the investor 30 % of the investment costs by year 15. In contrast, all of the silvopastoral systems provide an annual cash flow and, with the exception of one sandalwood scenario, had repaid at least 53 % of investment costs by year 15. Spotted gum is a fire resilient species; nonetheless, fuel loads in the spotted gum plantation will be higher than in silvopastoral systems, indicating higher wildfire risk.

The spotted gum and pine silvopastoral systems generated very similar LEVs; however, the composition of the returns differ. Income is more diversified in the spotted gum system, with 45 % of the LEV attributable to cattle. Only 27 % of the LEV is attributable to cattle in the pine system.

High teak establishment and management costs, coupled with this species' dense canopy shading out pasture, have resulted in teak silvopastoral systems being out-performed by spotted gum and pine silvopastoral systems, despite the relatively fast growth and high value of teak. In contrast, the slow growth and long rotation of vesi is largely responsible for the poor performance of the vesi and pine silvopastoral system.

Figure 17 Present value of investment costs and proportion of present value of investment cost paid back to the investor by year 15

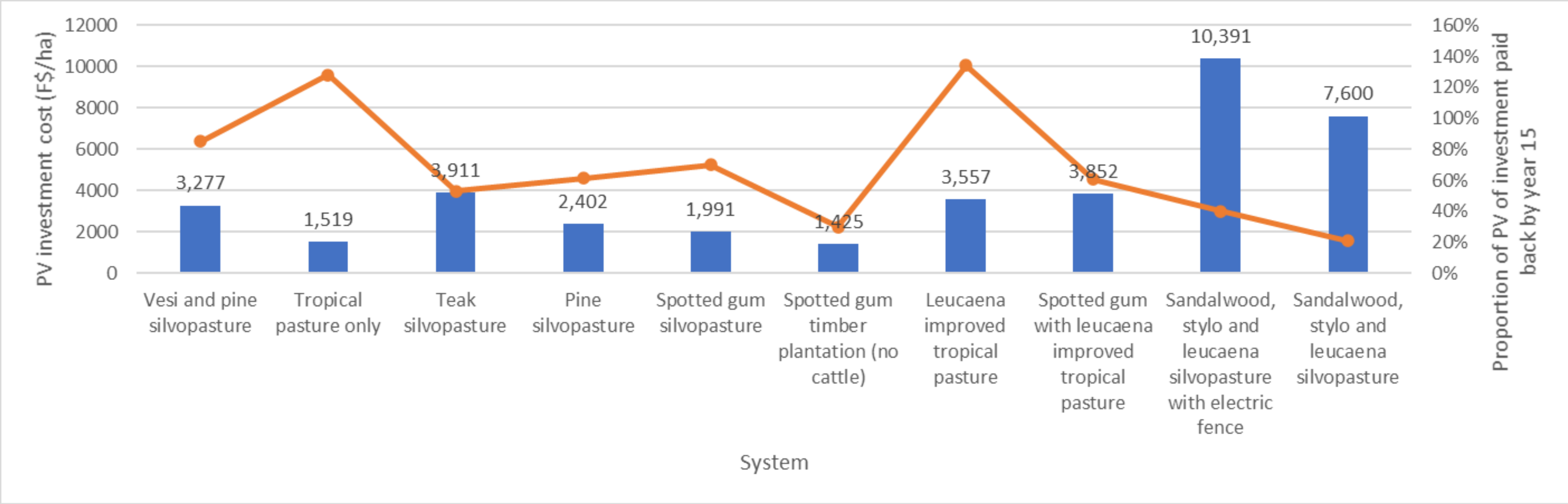
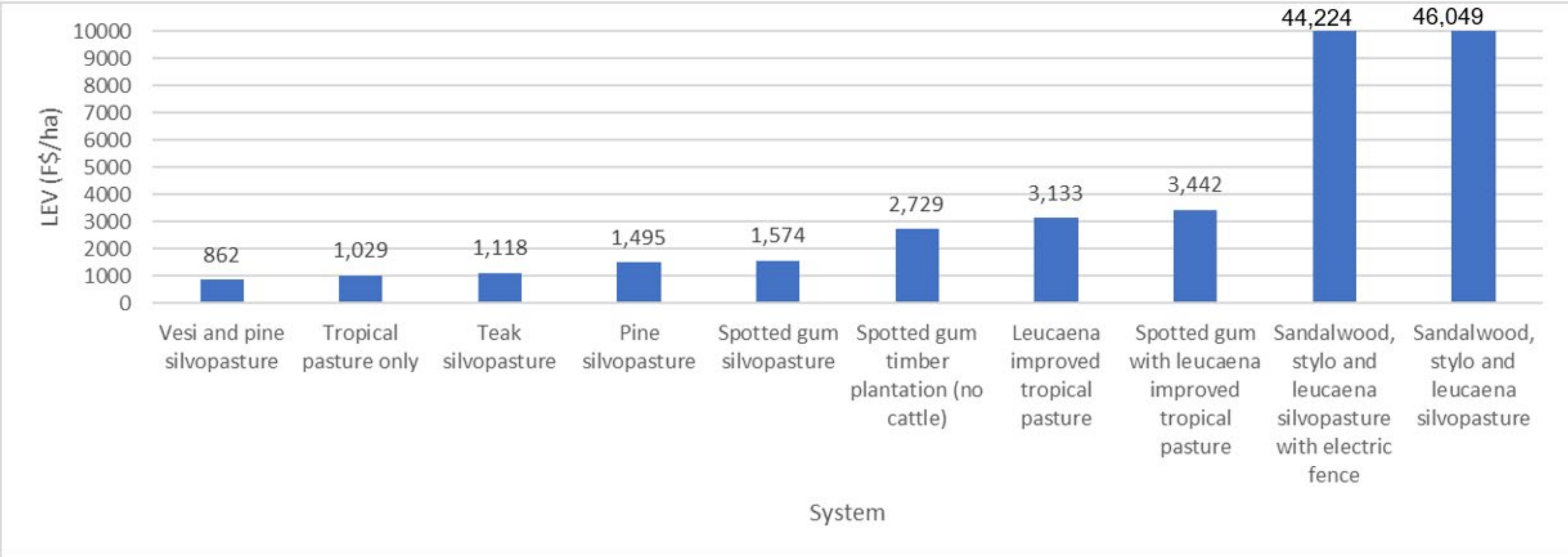


Figure 18 Land expectation value of modelled systems



7.3.1 Key findings from the financial analysis

The following summary of major findings from the financial analysis includes interpretation of key results from sensitivity analyses described in Appendix H that were performed on:

1. farm size;
2. sandalwood growth rate and price;
3. timber stumpage prices for non-sandalwood silvopastoral systems;
4. tree growth rates for non-sandalwood silvopastoral systems;
5. farmgate liveweight cattle prices; and
6. the discount rate.

- The minimum viable non-sandalwood silvopastoral system farm size on seasonally dry, sloping land in Fiji is about 22.5 ha if no water infrastructure is required and off-farm income (or income from adjacent agricultural land such as from growing cane) is available to cover management costs until trees are clearfall harvested. If water infrastructure is required, then the minimum farm size may be closer to 30 ha.
- If the silvopastoral system must cover all management costs throughout the rotation, then the minimum viable farm size in the study area is at least 75 ha, with 100 ha being a more sustainable minimum size by affording the business a buffer against poor seasons and variable farmgate prices.
- A 100 ha spotted gum silvopastoral system would require a present value of investment over the first 10 years of F$229,500, excluding any necessary water infrastructure. Therefore, establishment of silvopastoral systems in the study area will likely require a combination of long-term, low-interest rate loans, as well as material, financial and extension support from foreign donors, the Fijian government and non-government organisations.
- High projected returns to sandalwood silvopastoral systems need to be interpreted cautiously for several reasons.
    - Sandalwood LEV is extremely sensitive to sandalwood growth rate. If achievable growth on sloping, seasonally dry sites is 44 % less than the base case assumption of 0.7 cm/y, then sandalwood investments are not financially viable. Given the absence of empirical information for these landscapes, long-term growth trials are necessary to support decision-making.
    - Sandalwood systems require double the investment cost per hectare of leucaena improved tropical pasture systems, and almost four-times the per hectare investment cost of spotted gum silvopastoral systems. A 20 ha sandalwood silvopastoral system is expected to cost between F$152,000 and F$208,000.
    - Management of sandalwood trees over their lifetime requires 14 times more labour per hectare (1661 hours/ha) than managing the trees in a spotted gum silvopastoral system (121 hours). See Table F1 in Appendix F.
    - A 20 ha sandalwood silvopastoral system can support approximately 25 AE. Off-farm income will be required to supplement livestock income and cover management costs until the trees are harvested in about year 26.
    - Out of all modelled species in this analysis, sandalwood is the least resilient to wildfire throughout the rotation.
    - It may not be technically or biophysically feasible to establish large areas of sandalwood in these landscapes.

- Leucaena improved tropical pasture LEV exceeds all non-sandalwood systems under base case assumptions, except the spotted gum with leucaena system. This needs to be interpreted cautiously.
    - The financial performance of the leucaena system is very sensitive to farmgate liveweight cattle price. This is because there is no income diversification with timber and there are relatively high investment costs. If cattle prices are 30 % below the base case, then spotted gum and pine silvopastoral systems are better than the leucaena improved tropical pasture system. Further sensitivity analyses (that are yet to be performed) on pasture and leucaena growth rates would reveal a greater impact on the leucaena system than any silvopastoral system.
    - A sterile leucaena variety is not yet commercially available. Given the propensity for leucaena to become a weed, it may be prudent to be cautious about the widespread adoption of leucaena systems in Fiji until a sterile form is available.
- The tropical pasture only system represents a low-input, low-output land management option. This analysis clearly demonstrated the strong potential for investment in silvopastoral systems to improve landscape productivity. Pine silvopasture, spotted gum silvopasture and spotted gum with leucaena improved tropical pasture are projected to have financial performances that exceed tropical pasture only by 45 %, 65 % and 224 %, respectively.
- Under base case assumptions, if investors have a minimum acceptable rate of return of at least 12 %, then this can be satisfied by tropical pasture only, leucaena improved tropical pasture and sandalwood systems.
- Under base case assumptions, pine and spotted gum silvopasture systems can provide a 10 % return on invested funds.
- Under base case assumptions, teak and vesi silvopasture systems can provide an 8 % return on invested funds.
- Vesi does not appear to be a sound choice for silvopastoral systems in this landscape. At base case parameter levels, the returns to the tropical pasture only system exceeded returns to the vesi silvopastoral system. Even under optimistic stumpage price and growth rate projections, this species has equal or worse performance to spotted gum and pine at their base case stumpage price and growth rate levels.
- Teak is a high-risk choice in this landscape, given limited empirical data about growth rates in the study area and stumpage prices for Fijian logs. At base case parameter levels, teak silvopasture does exceed the tropical pasture only system. If base case stumpage prices or growth rates have been marginally overestimated, then teak LEV is negative. If stumpage prices or growth rates in this landscape have been under-estimated, then teak silvopasture is potentially the best-performing non-sandalwood system. Further research, including long-term growth plots, is necessary to support decision-making about teak in seasonally dry sloping lands of Fiji.
- Pine is a relatively low-risk silvopastoral system choice in the study area. There is a long history of pine plantations in this part of Fiji; however, there is little experience managing these plantings as silvopastoral systems. The sensitivity analyses generally highlighted that the pine silvopastoral system was expected to generate a lower LEV than a spotted gum silvopastoral system. The pine system generated less annual income from cattle than the spotted gum silvopastoral system, which may be an important consideration for a leaseholder choosing between these species. The only optimistic parameter setting that made the pine system more profitable than spotted gum was an increase in stumpage price of 40 %.

- Spotted gum is a moderate risk silvopasture system choice, because of the lack of growth and stumpage price information for Fiji. However, this lack of data is somewhat offset by the sensitivity analyses revealing that the LEV for this silvopastoral system was the most robust against changes to parameter levels. For example, owing to the relatively high cattle carrying capacity under spotted gum, this silvopastoral system was the only one that remained better than tropical pasture only with a 40 % increase in farmgate liveweight cattle prices. The relatively high cattle stocking also reduced the impact of low stumpage prices on LEV compared to the other silvopastoral systems.
- Out of the non-sandalwood silvopastoral systems, spotted gum appears to be the best-performer after considering the sensitivity analyses. However, long-term growth trials are necessary to support decision-making.
- The spotted gum plantation (no cattle) scenario was estimated to have a strong financial performance. Although spotted gum is a fire resilient species, fuel loads in the spotted gum plantation will be higher than in silvopastoral systems, suggesting higher wildfire risk. Furthermore, this plantation system generated no annual cash flows from cattle. Investors should be cautious about adopting plantation forestry in this landscape in the absence of effective fuel management practices throughout the life of the plantation (which has not been modelled).

7.4 Potential socio-economic impact of a 30,000 ha expansion of silvopastoral systems

Table 16 reports that the projected economic benefits of 30,000 ha of spotted gum silvopastoral systems. To put the projected increase in livestock numbers into perspective, the 16,000 AEs would represent a 13 % increase in the 2020 national herd of beef and dairy cattle; which includes ‘house cows’ and draught animals (FAO and Fiji Ministry of Agriculture, 2021). Given an average annual formal beef production between 2015 and 2019 of 3243 tonnes (https://www.statsfiji.gov.fj/latest-releases/key-stats.raw?view=download&fileId=6470), informal beef production of about 2000 tonnes per annum (Cole *et al.*, 2019), and assuming carcass weight is 50 % of liveweight, 30,000 ha of spotted gum silvopastoral systems in Fiji’s seasonally dry sloping lands have the potential to increase annual formal beef production by 25 % and annual total beef production by 15 %. With Fiji being only 43% self-sufficient in beef (Fiji Ministry of Agriculture, 2021), it does appear there would be strong domestic demand for increased beef production from spotted gum silvopastoral systems.

At full production, the expected annual timber production from 30,000 ha of spotted gum silvopastoral systems (1000 ha clearfall harvest, plus 1000 ha of commercial thinning per year = 142,200 m^3) would be equivalent to 33 % of Fiji’s average annual log production between 2015 and 2019 of 420,480 m^3 (https://www.statsfiji.gov.fj/latest-releases/key-stats.raw?view=download&fileId=1620). Together, the increase in beef and timber production would increase regional annual farmgate incomes by F$25,861,000. The total increase in regional incomes would be considerably higher given the accompanying expansion of ‘upstream’ and ‘downstream’ services, suppliers and value-adding activities not accounted for here.

The 30,000 ha expansion of silvopastoral systems in Fiji would directly generate at least 368 formal full-time equivalent regional jobs. The direct employment generation attributed to the management, harvesting and milling of spotted gum would be equivalent to a 15 % expansion of formal forestry industry employment in Fiji (Fiji Ministry of Forestry, 2021a). Substantial additional flow-on employment would be generated in the ‘upstream’ livestock and forestry services sectors (e.g. rural supplies, animal health, and seedling production), as well as ‘downstream’ marketing, meat processing and wood processing beyond primary sawmilling, which have not been accounted for in Table 16.

Table 16 Economic benefit of 30,000 ha of spotted gum silvopastoral systems

Statistic	Spotted gum silvopastoral system [1]	
	Cattle component	Timber component
Stock in 30,000 ha (AE cattle and m^3 timber)	16,000	2,204,100
Carbon stored in above and below-ground biomass (tC)		1,134,960
Annual production (kg/ha/y of marketable beef and m^3/ha/y of merchantable wood)	53.4	4.74
Annual production in 30,000 ha (kg/y of liveweight marketable beef and m^3/y of merchantable wood)	1,602,000	142,200
Annual farmgate production value from 30,000 ha (F$/y of marketable beef and $/y of merchantable wood)	7,209,000	18,652,000
Direct employment generation in livestock and forest management, and timber harvesting and sawmilling (full-time formal jobs) [2]	229	139

Notes: 1. All estimates assume 1000 ha in each spotted gum age class from one to 30 years.
2. Direct employment in cattle management is 16,000 AE / 70 AE/FTE. Direct employment in forest management on farms is 53 FTEs (30,000 ha x 101 hours/ha / 30 years / 1920 hours/FTE). Formal employment in commercial timber harvesting and milling is 86 FTEs (0.605 FTE/1000 m^3 x 142,200 m^3/1000).

By displacing imports and creating export opportunities to nations with a strong demand for spotted gum, such as Australia[6], these systems could help address Fiji's trade deficit in wood and paper products, which averaged F$80 million annually between 2015 and 2019 (https://www.statsfiji.gov.fj/statistics/economic-statistics/merchandise-trade-statistics.html).

The 30,000 ha of silvopastoral systems would be expected to permanently increase the storage of carbon on-site in these degraded landscapes by about 1.13 million tonnes (4.16 million tonnes of CO_2 e). The total carbon sequestration benefits would be substantially higher, given the storage of carbon in long-life wood products and displacement of high carbon-embedded substitutes such as concrete, steel, aluminium, plastic, and carpet. This carbon may find a buyer in a carbon market, which would substantially improve the financial returns to silvopastoral systems.

7.5 Challenges to expansion of silvopastoral systems

Several constraints to expansion of silvopastoral systems on Fiji sloping lands have been identified.

1. Responsibility for agroforestry in Fiji appears to be thinly spread among ministries and departments, and it 'falls through the cracks' from a policy perspective.
2. Existing policy or 'policy-like' statements with respect to agroforestry are generic. The potential is recognised but the range of options are rarely articulated. This suggests low awareness of the opportunities, limitations and challenges for commercial agroforestry systems, including silvopasture.

[6] *The failure of hardwood plantations in Australia, and the increasing politization of native forestry that has resulted in Western Australia and Victoria committing to shut down their industries before the end of the decade, will likely increase Australia's demand for imported hardwood timber.*

3. Where stronger commitments have been made, as in the case of the development of an 'agroforestry strategy' by MoF, there appears to be little institutional capacity or resourcing to act on these.
4. Opinion leaders are important in driving policy development, but without clear institutional mandates or resources, other priorities will prevail.
5. Sectoral divisions embedded in mandates exacerbate perceived barriers about agroforestry system components - as in the case of 'trees', 'livestock', 'land' and 'water'.
6. Sloping lands in Fiji are perceived and treated as unproductive, which acts as a deterrent to consideration in policy.
7. Due to degraded soils and modified disturbance regimes, most native timber species and mahogany are unlikely to be suited to seasonally dry sloping lands.
8. There is a lack of information about: (a) the range of pasture and tree species that are biophysically suited to sloping degraded land, and that will achieve beneficial species interactions; (b) the technicalities about how to grow particular species and species combinations; (c) product and market opportunities; and (d) the likely financial performance of silvopastoral systems.
9. Landholders face financial and labour constraints and may have limited access to germplasm for suitable crop, pasture and tree species. There may be other factors limiting availability of these important inputs.
10. Much of the sloping land is under traditional tenure and managed via the stewardship of the iTaukei Land Trust Board (iTLTB), which charges to establish leases, as well as annual rentals, which together act as an impediment to more productive use of sloping lands. During the pre-project visit to Fiji, the project team learned that some livestock projects have collapsed in Fiji because of payment arrears to the iTLTB.
11. Uncertainty about the risk of wildfire and cyclone damage, occasional drought conditions and issues surrounding perceived land tenure security is likely to be impeding silvopastoral system establishment on sloping land.
12. The low productivity of these landscapes means that large landholdings in a Fijian context (e.g. >100 ha) may be necessary for commercial viability.
13. The long payback periods in timber production mean that attracting private capital to establish trees in silvopastoral systems will be challenging without near term income streams, such as from carbon credits.
14. The aspirations and roles of men, women and youth in different communities, with respect to agroforestry components is not well understood.

7.5.1 Property rights

Land tenure insecurity in Fiji presents major barriers to commercial agriculture (Fiji Ministry of Agriculture, 2019; Griswold, 2021; Kamal Sharma *et al.*, 2021). Insecure property rights in land (and potentially trees), are inherently biased against any long-term investment, such as silvopastoral systems and other forms of agroforestry that involve long payback periods. For indigenous Fijians, traditional authority structures within the village are able to provide individuals with sufficient security to encourage farming investment on a commercial scale, although this is seldom done (Duncan, 2010). Furthermore, the absence of formal title to the land means that the land cannot be used as collateral for loans from commercial banks. The lack of long-term property rights for non-indigenous farmers has resulted in surplus cash being invested off-farm, not in building up the asset base and productivity of the farm (Duncan, 2010). Proposed reforms to property rights to land have met substantial opposition at the political level since 1959 (Ben and Gounder, 2019).

7.5.2 Conflict

Conflict and retaliatory actions, often arising from unclear land tenure or disputed land allocation processes (such as leasing), may result in crop destruction. Theft has reportedly become a pervasive problem for commercial farming (Duncan,2010), leading to a loss of interest in investment in farming, and changes in production from easy to steal crops (e.g. vegetables) to more difficult to steal crops (e.g. taro). In the case of silvopastoral systems with relatively high investment costs, and where returns are longer term (in the case of trees), or mobile (in the case cattle), the economic risk of conflict is greater.

7.5.3 Subsistence affluence (or subsistence guarantee?)

Subsistence affluence appears to be pervasive in Fiji (Duncan, 2010). That is, village communities can live comfortably by devoting only a few hours per week to food production and do not see it necessary to respond to income-generating opportunities, except to pay for essential services such as education and health. Duncan (2010) asserted that what underlies this behaviour is not well understood; but it should not be expected to change quickly or in response to agricultural policies and schemes that work well under completely different circumstances. Labour-intensive activities are unlikely to receive priority within the village context. However, COVID-19 has tested this theory, with observations of many people ‘returning to the farm’ for subsistence purposes, highlighting the value of access to land and knowledge about production, for resilience against future shocks, including climate change. In articulating options for transforming land to agroforestry for commercial purposes, care is needed to understand the consequences for rural land and societal transformation and impacts on important resources that guarantee subsistence (see e.g. Barney and Van Der Meer Simo 2021).

7.5.4 Integrated Systems

COVID-19 exposed the vulnerability of economies and production systems, but also elevated awareness of integrated approaches such as One Health, which point to agroforestry systems as solutions. Multi-product, multi- scale, multi-temporal systems are potentially shock-resilient and climate smart approaches that can provide immediate food needs, cash income from intermediate agricultural products as well as longer term security providing products for domestic and export markets.

8 Impacts

It is difficult to predict the potential impacts of this project given that no research in Fiji was possible outside the project development trip in October 2016 and the project planning meeting in December 2018. There was low engagement with Fijian stakeholders since 2019 due to the administrative restructure in the Ministry of Forestry and Covid-19. Nevertheless, some impact has been made through the desktop analyses performed.

The planning meeting, SWOT analysis and subsequent informal field discussion revealed a level or awareness about agroforestry and the absence of strong strategy or policy. Amongst the project team and Fijian participants from MoF and MoA associated with early work on the project, fruitful discussion potentially instilled a greater appreciation of the opportunity for commercial agroforestry in Fiji. The analysis and recommendations, if disseminated to the right people in Fiji, could influence institutional settings to progress agroforestry policy.

The spatial analysis performed as part of this project is the first attempt in Fiji to estimate the area where silvopastoral systems may be the highest value and best use of land. This analysis is preliminary and can be improved by collaboration with Fijian experts, as well as greater access to Fijian spatial data. Appendix C also lists datasets and Geographic Information System (GIS) software that would facilitate improved spatial analysis of suitability of land on Viti Levu and Vanua Levu for silvopastoral systems.

The research produced an expert-driven short list of five 'best-bet' tree species for silvopastoral systems on seasonally dry sloping lands in Fiji that are subjected to cyclones and wildfires. The research also designed silvopastoral system scenarios for the study area, including tree planting configurations and silvicultural regimes tailored for the different species. When possible, published growth models were used. However, preliminary tree growth models for vesi and spotted gum in Fiji were developed as part of this project, as was a cattle herd management mathematical model that accounted for declining pasture production under trees throughout the rotation. The financial models developed are expected to be beneficial for future research investigating benefits and costs of silvopastoral systems in Pacific Island countries (PICs). The model framework is also transferable to non-PIC contexts. All of these outputs are likely to be of interest to government and non-government organisations in Fiji and could generate impacts through their application to support future growth trials and research projects.

The specific financial performance estimates made in this project for a suite of silvopastoral scenarios on seasonally dry sloping lands in Fiji are the first published for silvopastoral systems in Fiji. Although model parameter estimates can certainly be improved through increased input from Fijian experts, species trials and further research, the investment costs, labour requirements and LEV estimates do provide valuable information to support investment decisions with respect to species selection, minimum viable commercial scale of operation and projected rates of return. A regional economic analysis has provided information about potential socio-economic impacts of silvopastoral system adoption, which can support Fijian decision-making about rural economic development policies and priorities.

9 Conclusions and recommendations

9.1 Conclusions

9.1.1 Agroforestry policy

While Fiji does not have a specific policy or strategy for agroforestry, there are strong policy-aspirations for the development and expansion of agroforestry generally as a land use. However, these are oriented towards different and sometimes converging goals, and there are conceptual complexities that present barriers in realising them. This is not unique to Fiji. These barriers can be summarised (drawing on Van van Noordwijk 2021) as:

- the segregation of "forestry trees" and "agricultural crops and livestock", ignoring the continuity in functional properties and functions of these often spatially aligned systems;
- the identification of agriculture with provisioning services and the assumed monopoly of forests on other ecosystem services in the landscape, challenged by the opportunity of "integrated" solutions at landscape scale;
- gaps in local knowledge of farmers/agroforesters as landscape managers;
- limited recognition of the contributions of social and ecological sciences; and
- the path-dependency of forestry, environmental or agricultural institutions, and emerging policy responses to "issue attention cycles" in the public debate, such as green-growth, climate change and reforestation.

This segregation of trees, crops and livestock is apparent in governance and ministerial mandates, and this impinges on progress for developing a single policy or strategy for agroforestry, as well as the advance of agroforestry technology. The Ministry of Agriculture (MoA) is responsible for livestock and crops, the Ministry of Forestry (MoF) for forests and trees, Ministry of Environment (MoE) for biodiversity, the Ministry of Trade (MoT) for products, the Ministry of Environment (MoE) focuses on climate benefits and the Ministry of Health (MoH) for food and health benefits. Our analysis suggests all see some value in integrated systems like agroforestry, but only MoF explicitly aspires to develop an agroforestry strategy and this does not currently appear to be funded.

Despite some apparent institutional divisions, there are some common spaces and institutional structures that are well-suited to mediate the development of an agroforestry strategy for Fiji. Existing policies, strategies, operational plans and laws, provide (and in some cases require) Ministries to work together, but getting agroforestry on the agenda needs policy-makers to prioritise it.

COVID-19 exposed the vulnerability of economies and production systems, but also elevated awareness of integrated approaches such as One Health which point to agroforestry as solutions. Multi-product, multi- scale, multi-temporal systems are potentially shock-resilient and climate smart approaches that can provide immediate food needs, cash income from intermediate agricultural products as well as longer term security providing products for domestic and export markets.

Agroforestry systems can be inclusive: they can be intergenerational production systems with elements attractive to men, women and youth. However, due consideration is needed of what and how people want to participate and whether adverse consequences could arise. Cash crops can have good and bad social, economic and environmental outcomes. Land use conflict can arise, as has been seen with poorly planned tree plantations in Fiji. The diversity of agroforestry elements necessitates good systems design - one model will not suit all. Addressing land-use rights and opportunities, as well as land tenure and crop security are essential.

Recent successes and lessons learnt elsewhere in developing agroforestry policies and strategies, such as in Africa, can point the way, but policy processes will need to change. Leadership and drive of departmental heads is critical in getting a policy issue on the government's agenda and moving it forward, but current top-down policy processes through which issues are progressed may need to accommodate greater community involvement in order to ensure adoption and sustainability. Lack of consolidated community support will affect policy support and implementation. While it is relatively easy to write policies by drawing inputs from internal and external advisors and experts, understanding the experiences of those whose practices the policies are trying to change is essential for effective agroforestry adoption.

9.1.2 Financial and economic performance of silvopastoral systems

A preliminary geospatial analysis of Viti Levu revealed 229,000 ha of sloping, seasonally dry, partially cleared forest or scrub with some agriculture and degraded land (Category 3 in Figure 8), where the opportunity cost of land use change is expected to be low and silvopastoral systems are likely among the highest and best productive uses. This land is separate from and greater in area than all land classified as agricultural land in the 2020 agricultural census of Fiji.

The financial analyses focussed on silvopastoral systems regarded by experts to be suited to the sloping, seasonally dry lands of Fiji, including being wildfire and cyclone resilient. The fact that there are tens of thousands of hectares of pine and mahogany plantations in Fiji suggests there are opportunities to make returns from long-rotation tree crops despite wildfire and cyclone risk. The financial analyses revealed the potential for strong returns on investment, with all systems evaluated generating positive land expectation values (LEVs) at a real discount rate of 8 %.

The LEV of sandalwood silvopastoral systems were an order of magnitude higher than the other systems evaluated. However, cautious interpretation is warranted, because there are uncertainties about sandalwood growth rates and market prices for plantation sandalwood in the study area. Also, relative to the other systems modelled, investment costs and labour requirements are much higher for sandalwood.

The financial performance of leucaena improved tropical pasture exceeded all non-sandalwood silvopastoral systems, except the spotted gum with leucaena system. Given the propensity for leucaena to become an environmental weed, caution may need to be exercised about widespread adoption of leucaena systems until a sterile form is available.

For non-sandalwood silvopastoral systems, 100 ha was found to be about the minimum farm size necessary such that all management costs could be covered by annual produce revenues, including an adequate farm household income. Pine and spotted gum were found to provide considerably better returns (internal rate of return of 10 %) than teak and vesi silvopastoral systems (internal rate of return of 8 %). Pine and spotted gum are also the most resilient to wildfire among the tree species evaluated.

A socio-economic analysis revealed that developing 30,000 ha (13 %) of the seasonally dry, sloping lands in Viti Levu into timber-cattle silvopastoral systems could expand national timber and beef production by 33 % and 15 %, respectively, while directly generating hundreds of formal full-time jobs and increasing annual regional farm-gate incomes by about F$26 million. Silvopastoral systems on under-utilised lands in Fiji have the potential to substantially contribute to several objectives described in the strategic plans of the Ministry of Agriculture and Ministry of Forestry, namely: (a) improving human health, food security, and rural employment; (b) poverty alleviation; (c) reducing trade deficits in agricultural and wood products; and (d) encouraging sustainable resource management, including by sequestering carbon and reducing soil erosion, flooding, landslide and wildfire risk.

9.2 Recommendations

To better understand the social, economic, geospatial and policy contexts of agroforestry in Fiji, there is a need to undertake research in Fiji with policy-makers, policy implementers, the agricultural and forestry industries, and the people who would be the target of agroforestry policy and measures for its implementation. Of particular importance are local people (men, women and youth) in different locations, who might adopt silvopastoral or agroforestry systems more broadly, and the other actors in the value chains that emerge.

This research has highlighted many substantial challenges to investment in long-term natural resource management projects in Fiji, with a focus on silvopastoral systems. These challenges can be addressed through collaborative future research targeted at developing innovative policies, institutions, partnerships, research methods, and resourcing mechanisms.

This research has provided a sound, but preliminary basis on which to assess the relative performance of silvopastoral systems in Fiji. There is a dearth of information about pasture, livestock and tree species growth and financial performance in seasonally dry, sloping Fijian landscapes. There is a need for long-term species trials, and this is strongly supported by Fijian government ministries, the timber industry and experts on Fijian livestock and forestry industries. In time, these trials could support decisions about which species to incorporate into agroforestry systems, inform ‘fine-tuning’ of management regimes, and greatly improve the precision of financial performance estimates.

Other necessary research priorities to assist efforts to overcome investment barriers in silvopastoral systems, include:

- engagement with communities where silvopastoral systems have high potential to seek to understand their social dynamics and aspirations;
- development of property rights frameworks to encourage long-term investment in agriculture;
- development of markets for ecosystem services (e.g. carbon sequestration) that are accessible to smallholders;
- evaluation of options for providing farms with access to year-round sources of water for livestock;
- improved geospatial assessments of land suitable for silvopastoral and other agroforestry systems;
- improved models for simulating pasture, livestock and tree growth, which would ideally be informed by long-term species trials;
- improved discounted cash flow decision support tools to inform policy-making and landholder management. For example, the models introduced by this research could be enhanced by working closely with Fijian partners to: (a) convert the models from deterministic to stochastic; (b) incorporate geospatial data to accommodate spatial heterogeneity in production potential; (c) accommodate wildfire and cyclone risk; (d) extend the models to account for other benefits, such as carbon sequestration; and (e) update growth models and financial data; and
- evaluation of opportunities for agroforestry, not only silvopastoral systems. In some parts of the sloping landscape examined in this study, the production of particular annual and perennial crops may be financially viable, and it would be informative for future research to evaluate these possibilities.

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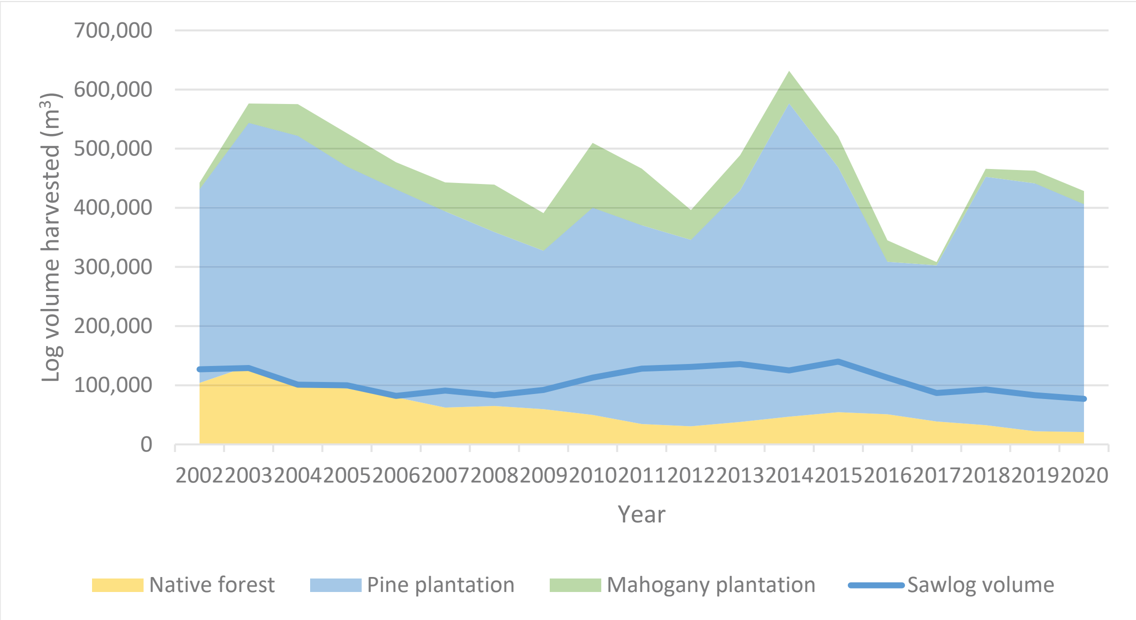
11 Appendixes

11.1 Appendix A: Brief background on timber and beef production in Fiji

11.1.1 Timber production in Fiji

Fiji has over 1.1 M ha of forests, with natural forests accounting for 86.6%, softwood plantations 6.8% and hardwood plantations 6.6% (Fiji Ministry of Forestry, 2021a). Over the period 1987 to 2004, log production in Fiji averaged 511,380 m^3 per annum, comprising 363,870 m^3 of exotic pine plantation logs, 141,540 m^3 native forest logs and 5970 m^3/y of exotic mahogany plantation logs (Fiji Department of Environment, 2010). Sawlog production in Fiji is reported as a category of total log production, and peaked between 1993 and 1998, with volumes exceeding 250,000 m^3 per annum (Fiji Bureau of Statistics, 2021). Total log volume by forest type, and total sawlog production between 2002 and 2020 is illustrated in Figure A1. The pine harvest volume sometimes varied substantially between years, but harvest levels in 2020 are about the same as they were in 2002, and averaged 361,140 m^3/y over this period. By 2020, harvested volumes for native forest and mahogany logs had both declined by 80 % relative to their peak volume over the period 2002 to 2020. Native forest and mahogany logs dominate sawlog volume. Only a fraction of the pine logs are processed as sawlogs with the majority being woodchipped for export. Consequently, sawlog production fell from 125,000 m^3 in 2014 to 77,000 m^3 in 2020, as the combined native forest and mahogany log supply contracted from 101,700 m^3 in 2014 to 43,100 m^3 in 2020. The reduced volume of native forest and mahogany sawlogs largely explains the reduction in annual log production value of the forestry and logging sector from F$55.1 million in 2014 to F$29.7 million in 2020 (Fiji Ministry of Forestry, 2021a).

Figure A1. Log volume harvested in Fiji between 2002 and 2020

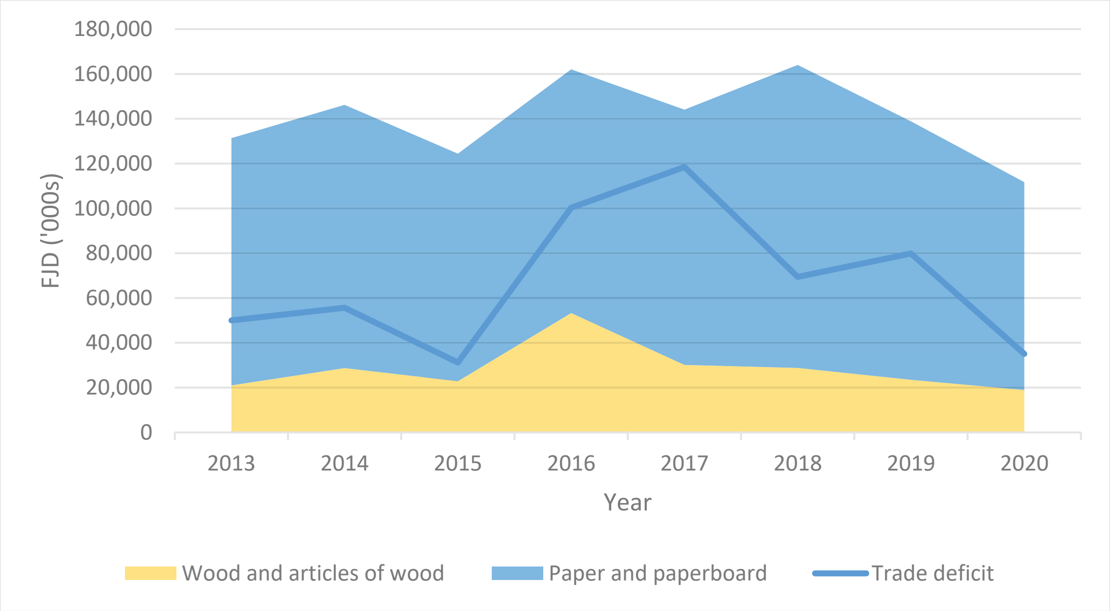


Sources of data: https://www.statsfiji.gov.fj/latest-releases/key-stats.raw?view=download&fileId=1620; and https://www.statsfiji.gov.fj/latest-releases/key-stats.raw?view=download&fileId=1882.

In 2018, the forestry sector, including forest management, harvest, sawmilling and furniture manufacture handled 406,000 m^3 of log and contributed F$158.7 million to the national economy, or 1.4 % of GDP (Fiji Ministry of Forestry, 2021a). Over the period

2013 to 2020, Fiji imported approximately the same value of solid timber products as it exported; about F$28.4 million/y. However, Fiji's main forestry sector export is pine woodchip (not solid wood), with an average annual export value of F$42.4 million over the period 2013 to 2020. As indicated in Figure A2, Fiji's import bill for paper and paperboard products manufactured from woodchips is much greater than the value of its pine woodchip exports, resulting in an average annual trade deficit in timber and paper products of F$67.5 million.

Figure A2. Fijian solid wood and paper imports, and the Fijian wood and paper product trade deficit (2013 to 2020)



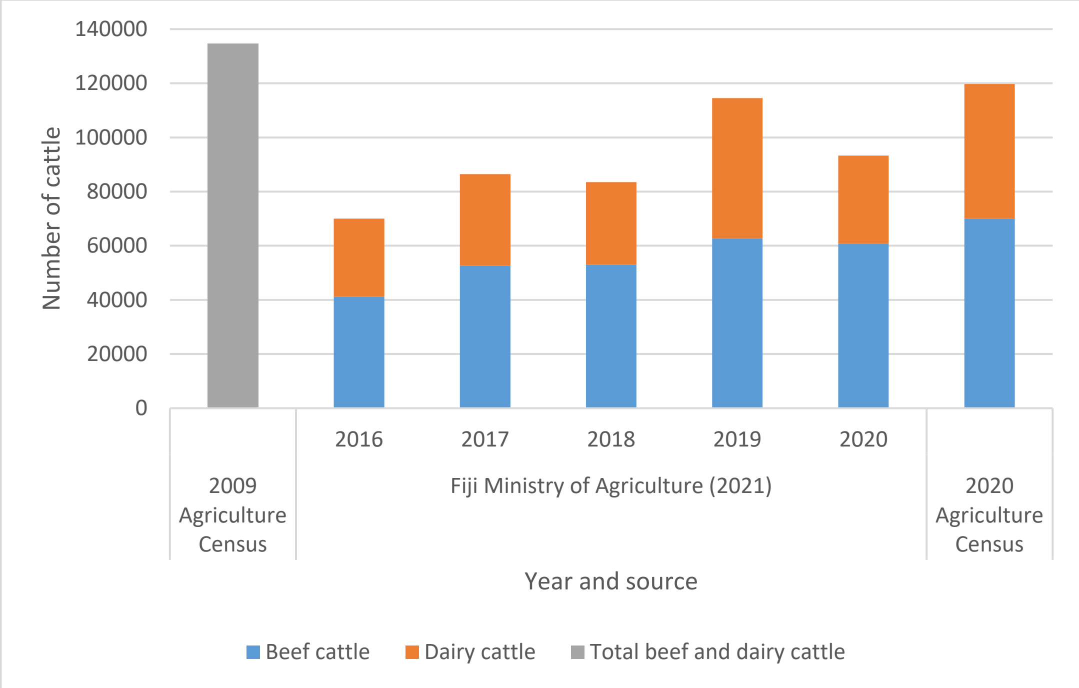
Source of data: https://www.statsfiji.gov.fj/statistics/economic-statistics/merchandise-trade-statistics.html

11.1.2 Beef production in Fiji

Duncan (2010) asserted that the beef and dairy industries have performed poorly in Fiji. Beef production peaked in 1971 with the slaughter of about 18,000 cattle in abattoirs. Over the decades since then, cattle raising moved away from large cattle projects towards smallholder and village production. Total numbers slaughtered in abattoirs have fallen by at least 50 % to between about 7000 to 9000 annually (Cole *et al.*, 2019), and 'bush slaughtering' has increased (Duncan, 2010). Over the period 2000 to 2020, Fijian annual beef production varied between 1960 tonnes and 3590 tonnes, with an average of 2510 tonnes (https://www.statsfiji.gov.fj/latest-releases/key-stats.raw?view=download&fileId=6470) .

Duncan (2010) attributed declines in cattle production to loss of and uncertainty about land leases. As indicated in Figure A3, the national cattle herd has fluctuated substantially in recent years There is a high degree of uncertainty about the national cattle herd, with the 2020 Agriculture Census estimate published by FAO (2021) being 28 % larger than the estimate published by Fiji Ministry of Agriculture (2021).

Figure A3. Fiji Beef and dairy cattle numbers for selected years



Sources of data: Cole et al. (2019); FAO (2021); Fiji Ministry of Agriculture (2021).

About 78 % of cattle are held in smallholder production systems where their importance is as draught animals or house cows, particularly in the cane sector. Commercial dairy cows make up 14 % of the nation's cattle, and commercial beef producers account for 8 %. Consequently, beef production in Fiji is typically a secondary output from cattle after draught and milk production, and Cole et al. (2019) determined that only 10 % to 15 % of slaughtered cattle were prime steers. An efficient system of middlemen acquires cattle from smallholders and delivers animals to government abattoirs run by the Fiji Meat Industry Board (FMIB), which amounts to about 7000 cattle per year, producing 2000 tonnes of commercial beef. There are no livestock markets and no market reporting service for cattle producers in Fiji owing to the small number of livestock traded in the formal meat sector. Informal beef production accounts for a similar number of cattle as the commercial sector, with high demand from the Muslim community for festivals, such as Qurbani. Fiji also imports 5500 tonnes of mainly low-quality beef and 1250 tonnes of beef offal. However, the tourist industry imports prime cuts. Domestic supply of beef meets between 35 % and 50 % of domestic demand (Cole *et al.*, 2019).

There is one large beef producer, Yaqara, with about 4500 cattle on Viti Levu. There are also about 50 smaller commercial herds averaging 70 head that exist within old coconut plantations on Vanua Levu and Tavenuni. The latter are considered to produce the best quality beef in the country. Although Yaqara and the small commercial cattle producers do have some improved pasture, the majority of cattle production in Fiji is informally grazed on vacant unimproved land and cane tops (Cole *et al.*, 2019). Calving rates at Yaqara and the smaller commercial farms are considered good, at about 60 % and 80 %, respectively. Cole et al. (2019) estimated cattle growth rates of 0.3 to 0.4 kg/day based on sale weights of three and four-year steers grazed on Fijian pastures without supplementary feeding. Selected statistics about cattle production in Fiji summarised from Cole *et al.* (2019) are reported in Table A1.

Table A1. Selected Fijian cattle industry statistics by beef sector segment

Beef sector segment	Number of farms	Average number of cattle per farm	Total cattle	Turn-off rate (%)	Calving rate
Yaqara	1	4500	4500	15	60
Small commercial beef producers	55	70	4000	20	80
Dairy farms	700	26	18000	5	50
Smallholders	21000	5	105,000	10	40

The following Fijian cattle market information has been summarised from Cole *et al.* (2019). The financial deal is between the middleman and the butcher, with the FMIB abattoirs provide slaughter services for a fee. Therefore, there are no published records of farmgate cattle prices. At the butchers, the supply of premium quality cattle is less than 20 % (excluding the South Pacific Butchery), which is said to be too small to warrant differentiation. There is no tradition of eating steaks in Fiji, with cooking methods chosen to make the meat tender. Fiji is predominantly a price-driven market where low-quality products dominate. At some butchers, middlemen can extract a price differential between a prime steer and a cull cow. At other butchers, there is no grading of carcasses, except to differentiate with small price differences between cattle under or over 400 kg carcass weight. The ceremonial or magiti market values cattle at between FJD800 to FJD1000 on the hoof, which is similar to the local wholesale market.

11.2 Appendix B: Report: Improving agroforestry policy for sloping land in Fiji: policy settings and recommendations

Please refer to separate report: Smith, H (2022) Improving Agroforestry Policy for Sloping Land in Fiji: Policy Settings and Recommendations, ACIAR project FST/2016/147, 59 p.

11.3 Appendix C: Report: A geospatial analysis of land suitable for agroforestry in Fiji

A Geospatial Analysis of Land Suitable for Agroforestry in Fiji

Jack Baynes
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August 2021

Executive summary

This report provides a partial response to the wider task of describing the opportunities and constraints for policy changes which would promote improved agricultural practices on sloping land in Fiji. In three parts, the report describes (1) datasets and Geographic Information System (GIS) software which would enable a spatial analysis of suitability of land on the islands of Viti Levu and Vanua Levu for agroforestry; (2) a preliminary aspatial analysis which indicates the way forward for an expanded investigation and (3) the social, cultural and commercial considerations which could preclude or enhance opportunities for the take-up of any proposed agricultural improvements by farmers. The results of preliminary modelling of social and cultural factors suggest that policy changes in support of agroforestry may be most successful if they are considered in terms of both the overall area of land and the number of sites on which trees could be grown. Protection from grass fires and distance from to roads or tracks emerged as major constraints. Also, the literature suggests that insecure land tenure is a major factor in farmers' motivation. Bringing proposed policy changes to fruition will depend on acceptance of Geographic Information System (GIS) modelling by the Fiji government. Hence, it is proposed that the next steps of any expanded investigation should be carried out by officers of the Fiji government. GIS training to produce a current land use map will be an important first step. In addition it is recommended that input should be sought from existing timber growers, purchasers and processors of forest products. Information about the commercial realities of agroforestry (e.g. maximum haulage distance) will assist further GIS modelling and proposals for consequent policy development.

1. Introduction

Purpose and scope of this report
The purpose of this report is to respond to the aims and objectives of Australian Centre for International Agricultural Research (ACIAR) project FST/2016/147.v3 'Improving Agroforestry Policy for Sloping Land in Fiji'. The overall aim of the project is to 'identify policy, institutional and governance–options to encourage adoption of sloping land agroforestry systems in Fiji, and provide decision-support information for government agencies, landholder communities and individual farmers on silvopastoral system design and expected financial and economic cost-benefit performance'.

The aim of the project is described in more detail as three objectives, of which Objective 2, – to 'identify potentially suitable sloping land areas … for selected areas of Viti Levu and Vanua Levu' – is addressed here. The required output for this objective is to describe the necessary, software, datasets, procedures, costs, required training and consequent expertise, opportunities for capacity building and usefulness and limitations of the analysis. A secondary output is a preliminary estimate of the land area suitable for silvopastoral or agroforestry systems. The justification for these outputs is the current dearth of spatial datasets, software and hardware which could be used to facilitate Fiji-wide land use planning. At present, the main software suite available to Fiji land use planners is 'VanuaGIS' which is restricted to visualising and querying existing (sometimes fragmented) datasets. Hence, creating new spatial datasets (particularly of current land use) together with their background attribute information, could be of great value to the Ministry of Forestry and Ministry of Agriculture. The key to achieving these aims will be to facilitate the development of mapping technical expertise in the two ministries in a context which reflects Fiji social and legal systems.

By design, the aim of the project acknowledges recent moves to integrate technical aspects of development assistance with social factors. World-wide, this began in the early 1980s when the failure of many development programs prompted a shift away from financing investment (roads and dams) to promoting policy reform (Dollar and Svensson, 2000; Santos-Montero and Bravo-Ureta, 2017). Concomitant with an awareness that developing countries could be held back by poor policies, was a new understanding that political, social and cultural factors needed to be better understood (Venugopal, 2018). Unfortunately, evidence from recent policy-based development programs indicates that the need to address social issues have not yet been learnt (see Baynes et al., 2021). In the field of integrated landscape management a persistent problem has been that successful small-scale interventions turned into win-lose situations as scale and social complexity increased (Reed et al., 2016). For this project, the challenge is to interpret the results of spatial modelling in the context of the most important quantitative and qualitative variables in Fiji. The credibility of any spatial modelling depends on a clear understanding of synergies or counter-balancing effects of the variables involved.

In Fiji, eighty four percent of the land is owned by indigenous Fijians through *mataqali* (clan) land owning units. Although the land maybe managed by government departments and statutory bodies, mataqali members retain significant power over its use. Thirty one percent of this land is accessible and cultivatable and is usually leased to non-Fijians. The balance is often in difficult terrain and of poor quality (Fonmanu et al., 2013; Murti and Boydell, 2008). The influence of climate and topography in differentiating the landscape into these two categories is visible in remotely sensed images. The mountains of Viti Levu and Vanua Levu create high rainfall wet zones on their windward sides and dry rain shadow zones on the leeward side. Rainfall is seasonal with a wet season from November to April and a dry season in the other months. Annual rainfall averages 2000mm in the dry zone and ranges from 3000 to 6000mm in the wet zone, as elevation increases from sea level at the coast to 1232m asl, in the mountains (FAO, 2003).

Although land may be leased out to community members, intra and inter-mataqali disputes arise over boundaries, lease payments, power grabs by influential community members and fencing-off of leasehold land. For forest management, conflict has led to delayed implementation of environmental management plans, impractical short-term leases for tree plantations and loss of mataqali social cohesion (Fonmanu et al., 2003). Conflict resolution has become a national issue and proposals for collective action in support of community or social forestry face significant obstacles (Murti and Boydell, 2008).

Hence, the challenge to the spatial analysis presented here is to model the spatial datasets (e.g. soil fertility) in a manner which is sensitive to the social forces which shape the landscape. For example, on land suitable for plantation forests, there may be little point in recommending community forestry on land which crosses mataqali boundaries, because they are managed by different tribal leaders and councils in accord with their own local customs. Qualitative variables including the security of land tenure and community support for collective or individual small-scale forestry are also important to assess. Quantitative variables including terrain slope, roading costs and haulage distances are also important to assess the capacity of the rural landscape of Fiji to support agroforestry.

This report continues as follows. Section 2 presents the background to GIS and the software, hardware, training and procedures which could be used for a spatial analysis. Section 3 provides examples of the outputs from each modelling step. The purpose of this section is to draw out any factors specific to the Fiji landscape which could lead to erroneous conclusions. Section 4 is a discussion of the results of the preliminary modelling, emphasising the need to interpret the results in terms of the social and cultural factors which may affect agroforestry policy reform. Integrating these factors at the beginning of any discussion of how to improve agroforestry uptake, may preclude a repeat of the top-down failures of the past.

2. Geographical Information Systems: Software, datasets, training and capacity building

2.1 GIS software

How GIS may help locate the land which may be suitable for agroforestry

An informal definition of a GIS is as a database that understands geometry. Spatial information is displayed as points, lines and polygons on a map, but the underlying database (e.g. land elevation and slope) are the 'attributes' which allow map features (e.g. a road) to be analysed. The road may appear as a line on a map, but its attributes may include its name and the nature of the paving. In the context of agroforestry in Fiji, this makes GIS a powerful landscape modelling tool. For example, a map of soil fertility, may be overlaid with a map of terrain slope. Land which is both fertile and flat may be presumed to be suitable for intensive agriculture. Hence, the most frequent use of a GIS is a simple thematic map. A caveat is that the end result is constrained by the accuracy of the datasets. For example, a landscape may have been originally covered with fertile soil which is mapped as that specific soil type. However, erosion may have moved most of the topsoil into the gullies. For this project, the purpose of the spatial analysis was to ascertain the location and area of land which may be most amenable to the uptake of agroforestry.

ArcGIS

World-wide, GIS software is dominated by the ArcGIS software suite marketed by the Environmental Systems Research Institute (ESRI). The company is based in the USA but has world-wide branches, including Australia. For thematic mapping, the ArcGIS Desktop software package is widely used in GIS offices in Australia, and Fiji. A key advantage of ArcGIS software is that it has near global data interoperability. Hence, the author has been able to combine datasets which originated in the Philippines or Papua New Guinea with datasets from the USA. Until recently, cost has been prohibitive for the typically underfunded GIS offices in developing countries. Fortunately, new open source and consumer friendly software has drastically reduced the cost of ArcGIS licences. A personal-use licence in Australia now only costs $AUD165 per annum (ESRI Australia, 2021). Free instructional videos have recently become available on YouTube.

In addition to the ArcGIS software suite, ESRI now provides ArcGIS Earth as a free download. ArcGIS Earth is very similar to the Google Earth (GE) platform which allows users to view landcover on any part of the globe. An ability to digitise polygons of land and to export them as Keyhole Markup Language (KML) files to other GIS platforms is an important feature. Whereas GE images often have cloud obscuring points of interest, the ArcGIS Earth image is almost cloud free.

QGIS
QGIS is a new Open Source Geographic Information System (GIS) licensed under the GNU General Public License. It runs on Linux, Unix, Mac OSX, Windows and Android and supports numerous vector, raster, and database formats and functionalities (QGIS, 2021). The lineage between QGIS and ArcGIS is clear. Operating windows, tools and visualisation are similar and facilitate migration from one system to the other. Also, the system is continually being upgraded ad be-bugged. For GIS laboratories, running ArcGIS on several computers and QGIS on every computer minimises cost and encourages users to be able to operate both systems. Free instructional videos are available on YouTube.

Google Earth
The North American company 'Google' is a partner in the operation of 13 SkySat satellites which collect high-resolution images of the world on a daily basis. Through their Google Earth (GE) platform, these images can be viewed and downloaded. Image resolution has improved in recent years to the extent that individual bushes can be distinguished in the rural areas of Viti Levu. GE is a free download and provides images which have been taken at different dates. For a tropical country like Fiji, this means that for any area of land which is covered with cloud, alternative images are available.

2.2 Datasets

SRTM digital elevation data
The NASA Shuttle Radar Topography Mission (SRTM) website provides digital elevation model (DEM) data, which can be downloaded, free of charge. The data are extraordinarily accurate, having a pixel or footprint size of one (latitude and longitude) second, or approximately 30m. The data have also been corrected for accidental 'spikes' and 'wells' and is geo-referenced to latitude and longitude coordinates and height above sea level (asl). The DEM consists of points on the ground which are defined in terms of their X, Y and Z values. X and Y values are recorded as map coordinates and the Z value is the height of each point asl. Hence the result is a dataset in which the 'footprint' is an array of X, Y and Z coordinates at a lateral spacing of (in this case) approximately 30 meters. The raw data set is then processed as images of land slope, aspect and elevation. These images may be created as raster (cell) datasets, similarly to digital photographs. Alternatively, they may be created as triangular irregular networks (TINs), i.e. a mesh of triangular facts.

In Fiji, the Land Use Planning Section of the Ministry of Agriculture has already used SRTM data to delineate land use Capability[7] (LUC) classes, in which land with a slope between 15-35 degrees is considered suitable for pastoral or forestry use, but not suitable for cultivation.

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[7]In the Fiji LUC system, land class V (16-20 degrees slope) is considered as 'moderately steep', class VI (21-25 degrees) is considered to be 'steep' and class VII (26-35 degrees) is considered very steep. Taken together, these classes are considered not suitable for arable cultivation, but suitable for pastoral or forestry use.

Google Earth images
GE was not designed for research purposes. However, images can be downloaded as jpeg files. The images themselves are not capable of being processed further. However, polygons (of any particular feature) can be created and exported as a KMZ file into ArcGIS or QGIS. The polygons become an essential component of a land use map which in turn becomes the key to decision-making about future land use.

Datasets from the ministries of Forestry and Agriculture
To date, no datasets have been obtained from the Fiji Ministry of Forestry and Ministry of Agriculture. These datasets (particularly cadastral boundaries) will be useful for an expanded project.

2.3 GIS procedures: Training, capacity building, data processing

The author's experience is that the basic procedures of GIS can be taught in a week. Follow-up practice is essential and it is preferable that trainees continue to use the software in their employment. From an ACIAR perspective, it becomes a win-win situation if the trainees are staff of both the Fiji Ministries of Forestry and Agriculture.

The broad principles of conducting a spatial analysis are:

- Defining the research question and the required outputs;
- Assembling the datasets, checking them for compatibility and deciding how the data will be presented;
- Undertaking the analysis and checkimg the results for scale errors and distortions; and
- Validating the results through ground-truthing, expert opinion and triangulation to other sources of information.

In an expansion of this project, the aim would be to train staff from the Ministry of Forestry and the Ministry of Agriculture and have them liaise to produce a map of current land use in Viti Levu and Vanua Levu, i.e. the dataset most necessary to assist decision making for an extended project. This is a necessary dataset in an extended project. Therefore it is essential that the land use categories be approved by both ministries.

For this project, it is suggested that the training should encompass:

- Classifying land into land use categories, as polygons in GE or ArcGIS Earth;
- Importing the polygons into ArcGIS or QGIS;
- Digitising new land use polygons over the top of the GE polygons so that the new polygons snap together to make a coherent and neat map;
- Creating raster datasets of slope, elevation and aspect from raw SRTM files;
- Importing whatever cadastral data is available from both ministries;
- Combining the datasets and querying them to construct maps of land and sites which may be most amenable to agroforestry;
- Refining the results so that they accord with known or anticipated social (e.g. national parks) and biophysical factors (e.g. grassfires, road access) which could encourage or negate their use for agroforestry;
- Aligning the output with the Land Use Capability (LUC) classes devised and published by the Land Use Planning Section of the Ministry of Agriculture;

- Ground truthing or triangulating the results to other sources so that errors due to different measurement units have not affected the results.

A highly desirable outcome of the training would be to emphasise that spatial analyses can be a useful tool, but image or 'layer' overlay can introduce errors in interpreting the results. For example, overlaying a dataset of steep land over a dataset of non-agricultural land may produce a useful map of land which are both steep and infertile. However, using many layers, (e.g. slope, elevation, aspect, cadastral data, soil fertility and rainfall) will result in a successive reduction of the land which is suitable according to the criteria. Continued subtraction results in a very low estimate of 'truly suitable' land. Hence, training should promote an interrogative mindset, e.g. is this land sufficiently fertile to warrant investment in agroforestry? Is this land fire-prone?

3. Undertaking the preliminary spatial analysis

3.1. Methods

For this preliminary analysis, datasets included jpg images from GE and the National Aeronautical Space Administration (NASA) Fire Information for Resource Management (FIRM) system. SRTM images were also downloaded from NASA and processed with Arc GIS. The purpose of the analysis was to ascertain the location, area and nature of land which might best be used for agroforestry. Because the area of Viti Levu is over one million hectares and the area of Vanua Levu is approximately half of that, it was not possible to conduct a full land use analysis of both islands. Hence a detailed investigation was confined in this case to Viti Levu.

GE and ArcGIS Earth were used to extract information about:

- Topography and vegetation of the two islands;
- Current land use;
- Evidence of annual grass fires; and
- Proximity of roads and tracks to potential agroforestry sites;

The FIRM data was used to corroborate the wide incidence of grass fires in the rain shadow areas.

Using SRTM DEMs, ArcGIS was used to extract datasets of terrain:

- Aspect (NE, SE, SW, NW);
- Elevation (meters asl);
- Slope (degrees).

The information in the datasets was used to assess the suitability of land in the two islands for agroforestry. This involved classifying land as either 'high rainfall', 'rain shadow', mountainous or flat; interpreting the GE images to assess the incidence of fire; assessing the influence of terrain slope and finally, identifying a typology of sites which may be suitable for agroforestry (or not).

3.2 Results

3.2.1 The topography of Viti Levu and Vanua Levu.

To describe what is early-childhood learning for Fijians, the landscape of the two major islands is divided into high rainfall terrain in the south and seasonally dry hills to the north of each island (Figure 1a, 1b).

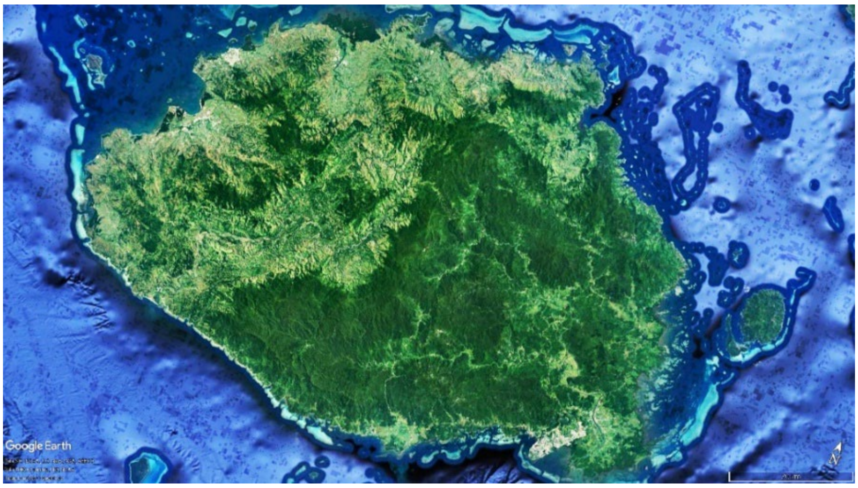

Figure 1a. High rainfall and rain shadow areas of Viti Levu

Figure 1b. High rainfall and rain shadow areas of Vanua Levu

The landscapes of both islands are similar, e.g. intensive agriculture on the flat costal lands of Viti Levu (adjacent to Suva in the south east and Nadi in the north west, Figure 1a) is replicated on the northern part of Vanua Levu (Figure 1b). Viti Levu has a mountainous centre whereas the orientation of the mountains on Viti Vanua is more directly north-south.

In contrast to the permanently green landscape in the southern parts of both islands, land in the rain shadow is seasonally dry and on Viti Levu, except for sheltered gullies and in remote high-elevation areas which have never been deforested, it is covered with bare earth, rock or grass (Figures 2 and 3). On Vanua Levu, this demarcation is less pronounced but land in the north is sufficiently dry (compared to the wet mountains in the south) to be used for sugar cane (FAO, 2003). On both islands, land may be delineated as either 'high rainfall' or 'seasonally dry'. Land may be further delineated by terrain slope, i.e. flat to rolling land on the coast and steep eroded mountains in the centre of both islands. Hence, on both islands, four broadly different landscape types and ecological niches exist as (1) flat/rolling and dry, (2) flat/rolling and wet, (3) steep and dry and (4) steep and wet. Agroforestry will consequently employ different suites of species, and different establishment and early age silvicultural regimes.

Figure 2. High elevation, eroded and dry landscape in the north of Viti Levu showing steep mountains as distinct from rolling hills and then pasture in the flatter foreground

Figure 3. Seasonally dry landscape adjacent to the town of Nadelei on Viti Levu showing steep eroded hill tops with a thin strip of vegetation in the gullies

3.2.2 Interpreting the GE and FIRM images to assess the incidence of fire

By implication, the high rainfall and rain shadow landscapes have widely different potential for agroforestry. The photograph of the farm (Figure 4), the FIRM image of the incidence of fires over one month (Figure 4) and the GE image of an individual fire (Figure 5), all reinforce the fire-prone nature of the rain shadow landscape. Given the propensity of fires to spread from one hillside to the next, i.e. into neighbouring farms (Figure 6), there is a positive motivation for individual landowners, to automatically protect their own homestead by burning off grass at the start of every dry season.

The key result of interpreting the GE and FIRM images is that the seasonally dry landscapes of both Viti Levu and Vanua Levu are susceptible to annual grass fires. Fire risk mitigation will be important for agroforestry in seasonally dry landscapes, including selecting tree species that can tolerate fire, keeping fuels low via livestock grazing, well-managed prescribed fire and adequate enforcement of fire policy.

Figure 4. Typical agricultural landscape showing sugar cane on flat land, sloping hills with gully vegetation and grass fire lit to protect a homestead

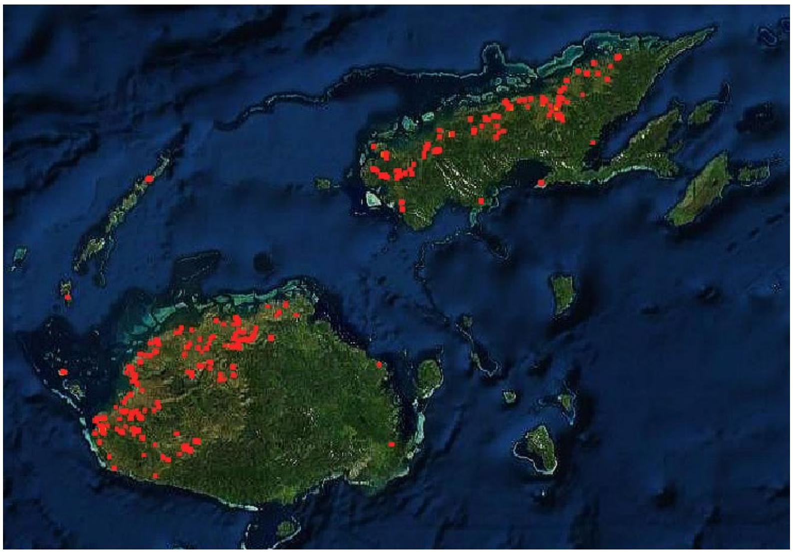

Figure 5. FIRM image of fire incidence (red dots) in Fiji during the month of July 2021

Figure 6. Grass fire of approximately 20 ha in the rain shadow terrain of Viti Levu

3.2.3 The influence of terrain slope

The Natawarau peninsula on Viti Levu provides an example of how modelling land suitability according to terrain slope may produce confusing results. The GE image shows the steep hillsides of the peninsula falling away to the coast line to the east and west (Figure 7). In principle, the flatter gullies would appear to be most useful for agroforestry. However, the SRTM image of terrain slope (Figure 8) shows that the gully has a similar slope (0-15˚) as the ridgetop. The ridgetop is likely to have thin eroded soil whereas the gullies are much more fertile. In addition, land in LUC class 5 (15-20˚, coloured light yellow) appears to be haphazardly interspersed with steeper land. Hence, calculating the area of land in one slope class is likely to provide a misleading estimate of overall site suitability for agroforestry.

Figure 7. GE image of the Natawarau peninsula showing the steep and dry landscape with small wetter gullies and intensive agriculture on the western side

A more complex landscape near Vakabuli in north western Viti Levu also illustrates the need for GE images to be used in tandem with SRTM models of terrain slope. The GE image (Figure 9) indicates that except for land adjacent to the town, most of the grazed paddocks appear to be suitable for agroforestry, particularly close to the town. The DEM (Figure 10) indicates that the terrain is much flatter there, although it may be eroded. Land to the south east is also potentially appropriate for agroforestry but the terrain is broken and partly steep. It is also untracked and plantation establishment there will be consequently expensive.

The main result of using terrain slope on Viti Levu to guide a classification of land suitability for agroforestry, is that flat land exists in two widely different ecological niches, i.e. hilltops and gullies. Flat land in the gullies is highly suitable for agroforestry but the preferred land use for landholders is probably cropping. Flat land on the hill tops is available for tree planting but the soils are highly eroded and susceptible to grass fires. Apart from the coastal lowlands, the terrain is broken and steep and roading costs on the steeper land will be high.

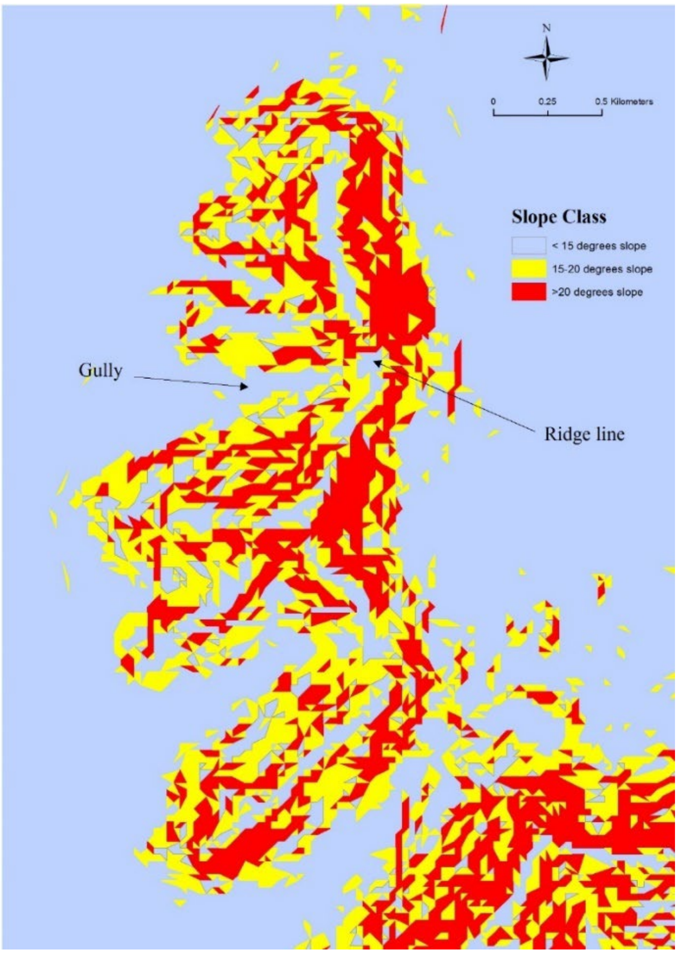

Figure 8. SRTM image of the slope of the Natawarau peninsula showing flat to rolling land on the ridge top and in the gullies

Figure 9. GE image of land adjacent to the town of Vakabuli in north western Viti Levu. Land potentially suitable for agroforestry has been outlined in the white polygon

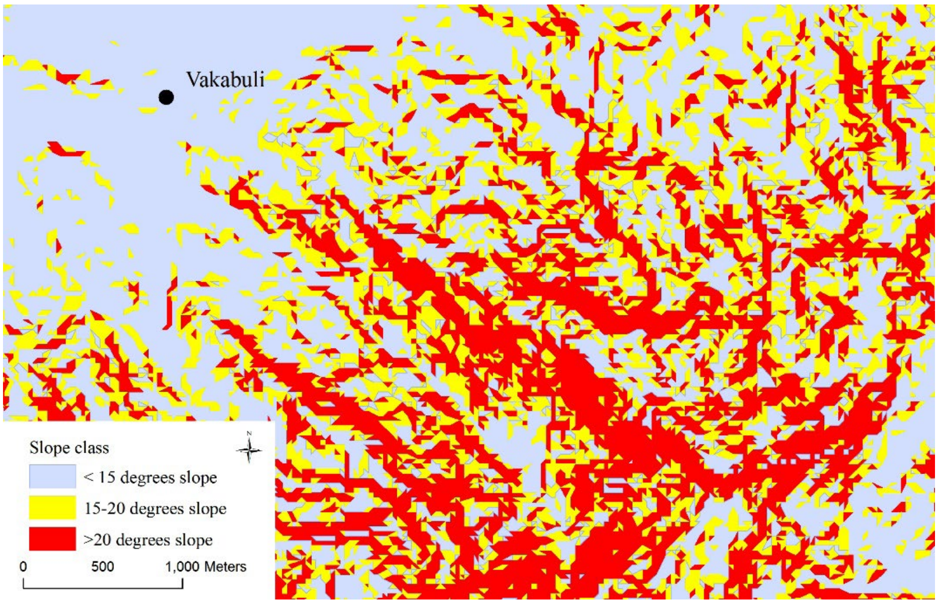

Figure 10. SRTM image of terrain slope adjacent to Vakabuli

3.2.4 Using the GE images to develop a typology of sites which may be suitable for agroforestry

If land which is currently used for agriculture is considered first, the GE images show that completely cleared land is dominated by intensely cultivated land (e.g. sugar cane) adjacent to urban areas and towns. The main area of interest is the margins of the urban areas or sugar cane farms which extend outwards as small-scale farms, e.g. in the south west of Viti Levu, (Figure 11).

To the south and north of Nadi, land further south has been parcelled out, either by sale or lease, to smallholders. Roads feed into the main highways to provides access to markets. Given the susceptibility of this seasonally dry land to annual grass fires (see Section 3.2.2) the suitability of this land for agroforestry is dependent on community-based fire management strategies.

A different type of land use exists in the central west of Viti Levu. Here, the terrain appears to be more arid, farms are more sparse and native forest or African tulip trees grow as tendrils of forest along water courses (Figure 12). Most hill tops are cleared, roads are few and the land appears to be degraded. Perhaps because of the low level of settlement, fires scars are fewer than in the grasslands of the north.

Figure 11. Small farms adjacent to the town of Kabisi in the south west corner of Viti Levu

Figure 12. Extensive clearing on ridge tops and regrowth or residual forest in gullies in the central west of Viti Levu

By area, the GE images indicate that the largest category of land which is not suitable for agroforestry is intact native forest in the south east of Viti Levu and the south of Vanua Levu (position ‘A’ in Figure 13). However, cut over or deforested land exists adjacent to these extensive intact stands (position ‘B’ in Figure 13). The main advantage of small-scale forestry on the latter areas of cut-over forest would be the absence of fire. However, much of the native forest and the land adjacent to it is steep and poorly roaded.

Figure 13. High rainfall landscape adjacent to the town of Wainiyavu in the central south of Viti Levu showing intact native forest (position 'A') and low-intensity land use (position 'B')

Different agroforestry regimes will apply (1) to land managed as intensely managed small-scale farms, (2) low intensity farms on more arid land and (3) high rainfall land adjacent to native forest. In the first example, agroforestry may be attractive to smallholders but the area of land devoted to it may be small. Intensive management of the farms depicted in Figure 11 suggests that agroforestry would be actively competing with other land uses. Harvesting will require amalgamation of forest produce over several (many?) woodlots to cover timber harvester's move-in costs. In the second example, (i.e. land depicted in Figure 12), tree planting is likely to restricted by a lack of road and track access. Although fires appear to be less frequent, fire control measures (infrastructure) are lacking. Notably, the government-owned plantation forest company (Fiji Pine) had not conducted tree planting on this land. The third example of land adjacent to high rainfall native forest (which is outside the project study area) is similar to the first example of intensely managed small-scale farms except that the high fertility and rainfall would encourage planting of high-value species, i.e. not commodity sawlogs.

The GE images suggest that land not suitable for agroforestry is highly developed agricultural land (e.g. sugar cane), closed canopy native forest and eroded rocky hills and mountains (discussed previously).

3.2.5 SRTM models of terrain elevation and aspect

SRTM models of terrain elevation and aspect added little to this preliminary spatial analysis (see Appendix 1). However, they may be useful for an extended analysis. Many agroforestry tree species have a well-defined elevation range in which they grow best. For example, *Gmelina arborea* grows poorly at elevations above 500m asl in Leyte, the Philippines. Similarly, *Paraserianthes falcateria* is susceptible to gall rust at low elevations on Mindanao. Hence, an SRTM model of elevation may be useful if new exotic tree species were to be considered in Fiji.

4. Calculating the area of each land use category

Using an ArcGIS Earth image of Viti Levu to classify land according to the categories identified in Section 3.2.4, resulted in six categories of dominant land use (Table 1). Polygons of land were digitised for each category across the landscape and the area of the polygons was totalled for each category. No attempt was made to apply cadastral criteria when sorting the polygons into each category. Hence, crossover between land use categories was sometimes difficult to determine as one land use graded into another. It was also not possible to establish land tenure.

Table 1. Area of six land use categories on Viti Levu

Land Use on Viti Levu		
Category definition	Area (ha)	Percent of total landmass
1. Developed agricultural land (e.g. sugar cane) and coastal urban areas (Figure 4)	175,000	17
2. Mixed agriculture on small farms (Figure 11)	34,000	3
3. Degraded and partially cleared forest/scrub with some agriculture (Figure 12)	229,000	22
4. Closed canopy native forest (Figure 13, position A)	486,000	48
5. Small farms adjacent to cut over and partially cleared high rainfall native forest (Figure 13, position B)	54,000	5
6. Eroded rocky hills and mountains (Figures 2 and 3)	61,000	6
Total (ha)	1,039,000	100

Mapping the six land use categories over the landscape of Viti Levu indicates where agroforestry might be most successfully located (Figure 14). In the north, agriculture is restricted to the wet season and apart from irrigated fields, land management is extensive (e.g. grazing) rather than intensive. In the dry season, the incidence of fire is high. Remote locations are poorly roaded.

Land devoted to sugar cane is largely located adjacent to Lautoka and Nadi in the north west, with intensive agriculture surrounding Suva in the south east. This land is too valuable for agroforestry, but the boundaries of this land present another scenario. Road density is high and protecting sugar cane with buffer strips of trees may provide better protection than *Imperata cylindrica* grassland.

The central west of the island is dominated by low intensity agriculture and the value of this land is less than the previous two categories. Agroforestry may be possible on cleared land adjacent to roads, but the overall site quality (e.g. a combination of soil fertility and rainfall) appears to be low.

Native forest dominates the south-eastern half of the island. Adjacent to villages, considerable parts of this forest has been cut over or cleared. Agroforestry may be possible there because the site quality is high and the risk of fires is low. However, the terrain is often steep and roading is minimal.

A concentration of smallholder farms is located in the south west. This land would appear to be highly suitable for agroforestry as separate woodlots. The risk of fire is high, but farmers often have unused portions of their land (steep or poor access) which they may be devote to a long-term, low maintenance crop.

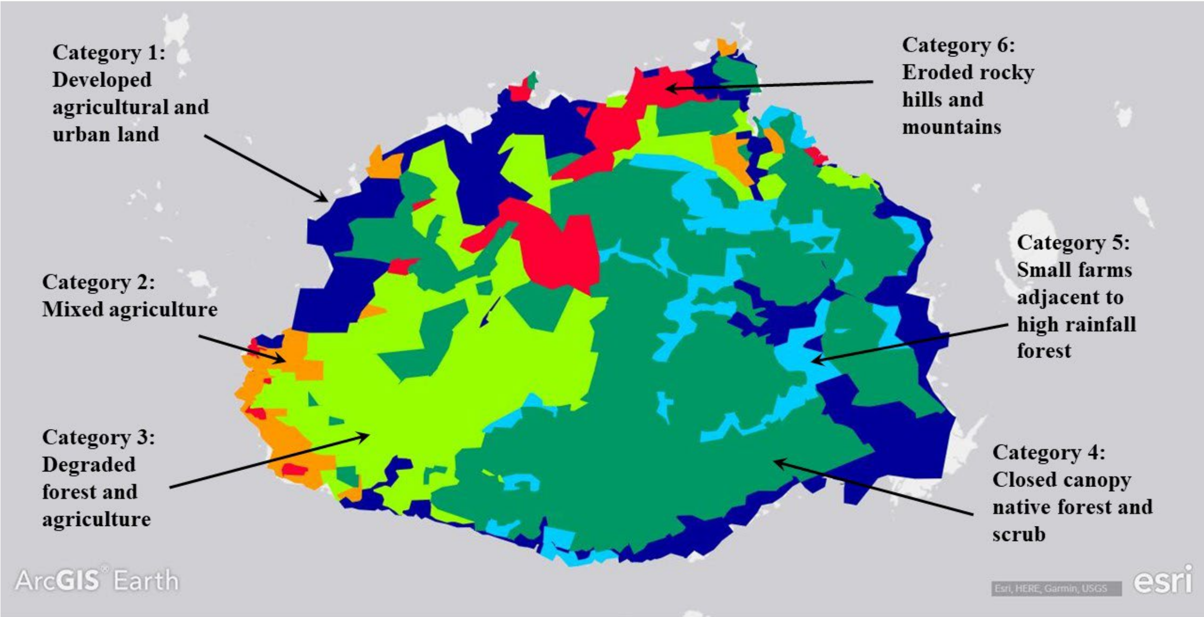

Figure 14. Location of six major current land use categories on Viti Levu.

Sorting the six land categories according to six suitability criteria for agroforestry provides an indication of the land which may be best targeted in an expanded investigation (Table 2). Because the land categories are variable and grade from one to another – and the suitability criteria are (deliberately) subjective – recommendations for the direction of an expanded investigation are also necessarily subjective. It is easier to exclude several land categories (e.g. closed canopy native forest), rather than to definitively include the others. The three positive recommendations are conditional. For example, highly developed agricultural land such as sugar cane is unsuitable, but adjacent land may be highly suitable, provided it can be leased at an appropriate rate. The author’s experience with these matters suggests that Figure 14 and Table 2 may provide general guidance but decisions concerning agroforestry will be made at a much more detailed, site by site, level. Hence, farmers will make individual decisions based on the traditional constraints which govern small-scale forestry in developing countries, i.e. land tenure, fire risk, road access, financial resources, community governance, government support and markets.

Table 2. Classification of six land use categories according to six criteria which determine their suitability for agroforestry

Land type						
Suitability criteria	*(1) Developed agricultural and urban land*	*(2) Mixed agriculture*	*(3) Degraded forest and agriculture*	*(4) Closed canopy native forest and scrub*	*(5) Small farms adjacent to high rainfall native forest*	*(6) Eroded rocky hills and mountains*
Rainfall	High rainfall or irrigated	Sufficient for seasonal crops	Variable	High	High	Seasonally low
Site quality	Very high	High to low	Variable, often low	High	High	Very low
Fire incidence	Protected	Variable	Frequent	Negligible	Low	Unknown
Terrain slope	Predominantly flat	Variable – steep terrain is not usually cropped	High variation over small areas	Steep and variable	Steep and variable	Steep
Road access	High	High	Often poor as distance from nodes extends	Poor to non-existent	Poor to non-existent	Poor
Proximity to processors	High, at Lautoka and Nadi	High, south of Nadi	Low	Low	Low	N/A
Overall suitability	**Highly suitable on sloping land adjacent to developed agriculture, if protected from fire**	**Suitable for small areas of unused land on individual farms, if protected from fire**	**Suitable if protected from fire**	**Unsuitable (remnant forests)**	**Unsuitable (higher value horticulture opportunities)**	**Unsuitable (very low site quality)**

5. Recommendations for an expanded investigation

This highly pictorial representation of land use types provides objective evidence of land use. Hence it provides a sound basis for tentative recommendations for a widened investigation. A limitation of this report is the absence of qualitative input from Fiji nationals. This means that those factors which are well understood by them – are absent here. This information may relate to social aspects such as the capacity of mataqali members to undertake collective action, the power relationships and social organisation and interaction of government agencies and mataqalis. For example, any discussion of agroforestry requires consideration of land tenure for long-term crops (i.e. trees). Fire control is necessary for agroforestry, particularly during establishment, and this requires broad community support and compliance. Hence any discussion must widen to include the social forces at play on any proposed site. It is proposed that the next steps of any expanded investigation should be carried out by officers of the Fiji government. GIS training to produce a current land use map will be an important first step

Ultimately, agroforestry policy changes will be driven by a reinterpretation of the priority zones and suitability criteria presented in Figure 14 and Table 2. Policy change will also require a wide range of stakeholder input from organisations such as Fiji Pine. From a government perspective, the spatial analysis presented here, may answer questions about current land use, i.e. the status quo. However, the aim of ongoing research should be to support decision-making about what land use is desirable and possible in the future. GIS can help to answer these questions, but datasets of roading, mataqali boundaries and other cadastral data will be required. Agricultural cooperatives may be able to provide information about their members (e.g. addresses) which may allow targeted agroforestry extension assistance. Hence a further recommendation of this report is to include as wide a range of stakeholders as feasible in an expanded investigation. From a GIS modelling perspective, this would improve the quality of attribute data in spatial databases. For example, sawmills will have maximum haulage distances from which they are prepared to source logs. Including these factors will ensure the validity of spatial modelling. For any proposed policy changes, including a wide range of stakeholders is simply a matter of practical politics.

Finally, GIS is a useful tool for thematic mapping and modelling, but it can provide questionable results. Rather than modelling areas of land, it may be better to ascertain the number of sites (e.g. farms) and the clientele who may be motivated to engage in agroforestry. From a wood processors perspective, aggregating log purchases from large numbers of adjacent woodlots may be financially feasible whereas widely scattered woodlots may not. Hence, the final recommendation is that an expanded investigation should link spatial data to as much attribute data (e.g. sites, haulage distance, roading) as possible. The database may then become highly attractive to other government agencies.

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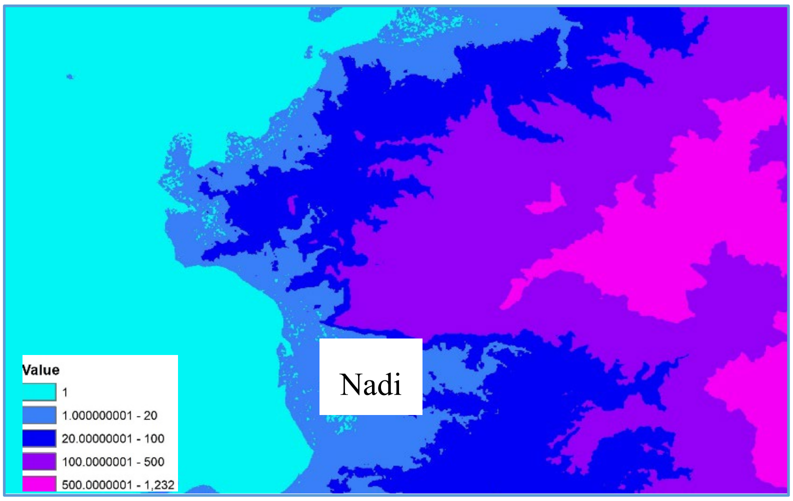
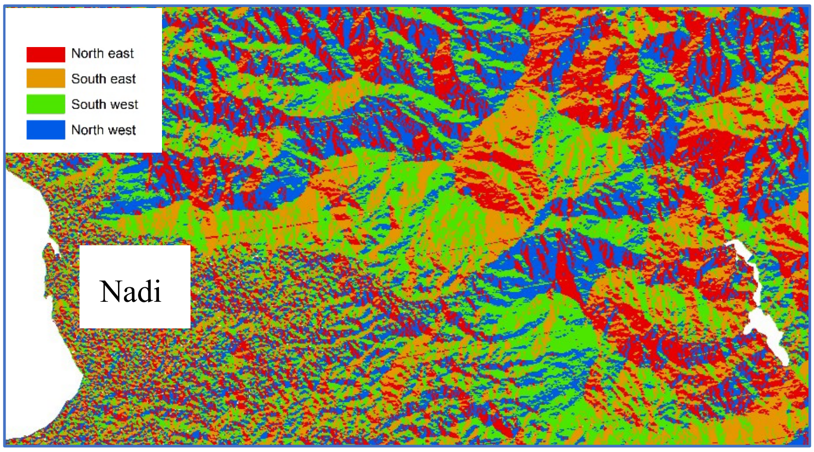
Appendix 1. GE and SRTM images of terrain elevation and aspect of land surrounding the city of Nadi

(a)



(b)



(c)

Figure 15. (a) GE image of high land use intensity adjacent to the city of Nadi, surrounded by a steep escarpment; (b) SRTM model of land elevation (m, asl); (c) SRTM model of terrain aspect

11.4 Appendix D: Expert group and their recommendations for species selection

11.4.1 Experts invited to participate in assessment of tree species

	Full Name	Organisation
1	Maika Tabukovu *	Fiji National University
2	Sairusi Bulai	former The Pacific Community (SPC)
3	Sanjana Lal	Fiji Ministry of Forestry
4	Marika Tuiwawa *	University of the South Pacific (USP)
5	David Lee *	University of the Sunshine Coast
6	Vinesh Prasad *	Former ACIAR and SPC employee
7	Kevin Glencross *	Southern Cross University
8	Solomoni Nagaunavou	Fiji Ministry of Agriculture
9	Lex Thomson	University of the Sunshine Coast
10	Tony Page *	University of the Sunshine Coast
11	Deborah Sue	Fiji Ministry of Forestry
12	Steven Walker	Former Ridge to Reef Coordinator
13	Isaac Rounds	Conservation International
14	Tevita Bulai	Fiji Ministry of Forestry
15	Digby Race	University of the Sunshine Coast
16	Vinesh Kumar	Fiji Ministry of Agriculture
17	Jalesi Mateboto	The Pacific Community (SPC)
18	Maleli Nakasava	Fiji Ministry of Forestry
19	Shipra Shah *	Fiji National University
20	Apisai Rinamalo *	Fiji Ministry of Forestry
21	Asesela Cokanacagi *	Fiji Pine Limited
22	Semi Dranibaka *	Fiji Hardwood Corporation Limited
23	Mark Dieters *	The University of Queensland

Note: * Indicates experts who agreed to participate.

11.4.2 Full list of 98 tree species reviewed by experts with expert recommendations regarding suitability for planting on seasonally dry sloping lands in Fiji

U = unsure; NS = not suited; M = mixed (some respondents classified NS and some S); S = suited

Scientific name	Fiji name	Other common or trade names	Native or exotic	Expert assessment of species suitability			
				U	NS	M	S
Acacia auriculiformis		black wattle	Exotic				1
Acacia crassicarpa		northern wattle	Exotic				1
Acacia koa		koa	Exotic	1			
Acacia mangium		mangium	Exotic				1
Acacia spirorbis			Exotic	1			
Albizia lebbeck		Siris tree	Exotic	1			
Artocarpus altilis	buco, uto	Breedfruit	Exotic	1			1
Aquilaria spp.		Agarwood, eaglewood	Exotic				1
Azadirachta indica		neem tree	Exotic				
Canarium indicum		canarium	Exotic		1		
Cananga odorata	Mokosoi	Cananga, Ylang-ylang	Exotic				1
Coffea arabica		Coffee	Exotic				1
Dalbergia cochinchinensis		Thailand Rosewood	Exotic	1			
Dalbergia barrensis		Rosewood	Exotic				1
Diospyros spp			Exotic	1			
Carica papaya		Papaya	Exotic				1
Citrus spp.			Exotic				1
Corymbia citriodora subsp. variegata		Spotted Gum	Exotic				1
Corymbia citriodora subsp. citriodora		Spotted Gum	Exotic				1
Corymbia hybrid (Corymbia citriodora x torelliana)		Spotted Gum	Exotic				1
Endospermum medullosum		Whitewood	Exotic		1		
Eucalyptus camaldulensis		river red gum	Exotic	1			
Eucalyptus cloeziana		Gympie messmate	Exotic				1
Eucalyptus deglupta		rainbow gum	Exotic	1			
Eucalyptus grandis		flooded gum	Exotic		1		
Eucalyptus pellita		red mahogany	Exotic				1
Eucalyptus pilularis		blackbutt	Exotic		1		
Flindersia brayleyana		Queensland Maple	Exotic		1		
Gliricidia sepium		Gliricidia	Exotic				1
Khaya senegalensis		African Mahogany	Exotic				1
Leucaena leucocephala		Leucaena	Exotic				1

Mangifera indica		Mango	Exotic				1
Persia americana		Avocardo	Exotic		1		
Pinus caribaea var. hondurensis			Exotic				1
Pterocarpus indicus	vaivai vavalagi	rosewood, narra	Exotic		1	1	1
Santalum album		Indian sandalwood	Exotic				1
Santalum yasi x album hybrid		sandalwood	Exotic				1
Samanea saman (Albizia saman)	Vaivai-Ni-Veikau	Rain tree, Mokeny pod tree	Exotic				1
Spathodea campanulata		African Tulip	Exotic				1
Swietenia macrophylla (Prov. Costa Rica)		big-leaved mahogany, Honduran mahogany	Exotic				1
Tectona grandis		teak	Exotic				1
Theobroma cacao		Cocoa	Exotic	1			
Thespesia populnea		Seychelles rosewood, large-leaved tulip tree	Exotic	1			
Acacia richii	Qumu		Native	1			
Agathis macrophylla	Dakua Makedre	Pacific Kauri	Native				1
Alphitonia zizyphoides	Doi		Native				1
Barringtonia edulis	Vutu		Native		1		
Bischofia javanica	Koka	Java Cedar	Native		1		
Buchanania attenuata	Maqo ni Veikau		Native	1			
Calophyllum inophyllum		beach mahogany, Alexandrian laurel	Native		1		
Calophyllum neo-ebudicum	Damanu	Poon, Penaga, Bitanghol, Bitaog, Tanghon	Native	1			
Cananga odorata	Makosoi		Native	1			
Casuarina equisetifolia	Nokonoko	sheoak	Native				1
Cinnamomum spp.	Macou		Native		1	1	1
Cocus nuifera		Coconut	Native		1		
Cordia subcordata	Nawanawn		Native				1
Dacrycarpus imbricatus	Aumunu		Native	1			
Dacrydium nidilum	Yaka	Ekor kuda, Fijian dacrydium, Huon pine, Malor, Melor, Rimu, Ru bukit, Sempilor, Srol kraham, Yaka, masiratu	Native	1			

Degeneria vitiensis	Masiratu		Native	1			
Dillenia biflora	Kuluva		Native	1			
Eleocarpus spp.	Kabi		Native		1		
Endiandra gillespiei	Damabi		Native		1		
Endospermum macrophyllum	Kauvula	Pacific Whtewood, Ekor, belangkas, Gubas, Sendok Sendok, Terbulan	Native		1	1	1
Endospermum robbienum			Native		1		
Emmenosperma micropetalum	Tomanu		Native				1
Fagraea Gracilipes	Buabua	Urang, Temasuk, Tatrao, Trai, TamSao, Tembesu, Anan and Ananma	Native	1			
Flueggea flexuosa	namamau	poumuli	Native				1
Garcinia pseudoguttifera	Bulu M		Native	1			
Gmelina Vitiensis	Rosawa	White beech	Native	1			
Gymnostoma vitiensis	Velau		Native	1			
Gyrocarpus americanus	Wiriwiri		Native	1			1
Gonystylus punctatus	Mavota		Native	1			
Haplilobus floribundus	Kaunigai		Native	1			
Hernandia olivacea	Dalovoci		Native	1			
Heritiera onithocephala	Rosarosa		Native	1			
Intsia Bijuga	Vesi	Merbau	Native				1
Inocarpus fagifer	Ifi	Tahitian chestnut	Native		1		
Kingiodendron platycarpum	Moivi		Native	1			
Metroxylon vitiense	ota	Fiji sago palm	Native	1			
Morinda oleifera			Native	1			1
Morinda citrifolia	noni	Indian mulberry	Native				1
Myristica spp (kaudamu)	Kaudamu	Darah Darah, Duguan, Kumpang, Mutwinda, Penaraham, Tambolau, Nutmeg	Native	1			
Palaquium Fidjiense	Bauvidi	Bauvidi Nyotah, Janter, Nato, Njatuh, Pencil Cedar and Red Silk	Native	1			
Palaquium hornei	Sacau		Native	1			
Palaquium porphyreum	Bauvudi		Native	1			
Pandanus spp	sa'aga		Native	1			
Parinari insularum	Sa		Native	1			
Planchonella grayana	Bausa		Native	1			

Podocarpus neriifolius			Native	1			
Pometia pinnata	fao, fava	oceanic lychee	Native	1			
Retrophyllum vitiense	Dakua Salusalu	Masiratu	Native	1			
Santalum yasi		Sandalwood	Native				1
Santalum yasi x album hybrid		sandalwood	Exotic				
Santalum sp							
Schefflera seemanniana	Sole		Native	1			
Serianthes spp	mamufai, vaivai		Native				1
Sterculia vitiensis	Waciwaci, Marasa		Native				1
Syzygium decussatum	Yasimoli, yasiyasi		Native				1
Terminalia catappa	tavola	tropical, beach, sea or Indian almond	Native				1
Xylopia pacifica	dulewa		Native		1		

11.4.3 Introduction email to tree species experts

Requesting your participation in ACIAR project: **Improving Agroforestry Policy for Sloping Land in Fiji**

Dear

I am writing to you to seek your input into the Australian Centre for International Agricultural Research (ACIAR) project ADP/2016/147 – Improving Agroforestry Policy for Sloping Land in Fiji. We have spoken previously in relation to Fiji tree planting programs, and I believe your expertise would be valuable in relation to the technical aspects about tree species that are biophysically suited to grow on Fiji's seasonally dry sloping land, and suited for silvopastoral production systems.

By way of background, some general information on the project and study area is provided below.

The Project

The project is designed to provide information to decision-makers in government and industry about silvopastoral systems on underutilized Fiji sloping lands. The project focusses on exploring opportunities and constraints to the expansion of silvopastoral systems including:

a) the range of pasture and tree species that are biophysically suited to degraded sloping land;
b) the technicalities about how to grow particular species and species combinations;
c) product and market opportunities; and
d) the likely financial performance of silvopastoral systems.

The Study Area

The attached map shows the four Divisions of Fiji, with seasonally dry regions occurring within the Western and Northern Divisions.

The focus area for this study is sloping land within the seasonally dry zones of western and northern Viti Levu and Vanua Levu (referred to in some literature as the talasiqa lands) with slopes of 12-25 degrees (primarily classes IV – VI under the Fiji Land Use Capability Classification), which makes them unsuitable for cultivation.

The intermediate seasonal zone that occurs between the dry and wet forest ecoregions is not being considered in this study. The intermediate zone includes Rakirakie (in Ra province) in the north, and Sigatoka (in Nadroga-Navosa province) in the south of Viti Levu.

Climate of the seasonally dry sloping lands.

The orientation of Fiji’s mountains combined with the southeast trade winds produces a rain shadow to the northwest of mountain areas resulting in a tropical climate with hot humid ‘summers’ and relatively dry ‘winters’.

Rainfall in the study area varies from 1500-2250 mm per year, but is strongly seasonal, with most rain falling during the December-April ‘summer’, while dry conditions prevailing during the cooler remainder of the year. Table 1 shows monthly temperature and rainfall for Nadi and Lautoka, which are within the seasonally dry zone. Statistics for Suva, which is not within the seasonally dry zone, are also provided for comparison. The average annual rainfall in Nadi (1,809 mm) and Lautoka (1,868 mm) is much less than in Suva (3,041 mm).

Cyclones coming from the northwest hit the islands between November-April every few years. This will be an additional climatic factor to consider.

Table 1. Monthly average rainfall at Nadi and Lautoka, and Suva for comparison; and average maximum and minimum temperatures for Nadi and Suva.

	Lautoka	Nadi				Suva			
	Rainfall (mm)	Ave. max. temp. (°C)	Ave. min. temp. (°C)	Rainfall (mm)	Rain days >0.1 mm	Ave. max. temp. (°C)	Ave. min. temp. (°C)	Rainfall (mm)	Rain days >0.1 mm
January	298	31.6	22.7	299	18	30.6	23.6	315	23
February	303	31.5	23.0	302	18	31.0	23.8	288	22
March	322	31.1	22.6	324	19	30.6	23.5	371	23
April	170	30.6	21.7	163	12	29.7	23.1	390	22
May	86	29.8	20.1	78	7	28.3	21.9	267	20
June	70	29.2	19.3	62	6	27.6	21.4	164	18
July	47	28.5	18.3	46	5	26.5	20.4	142	18
August	60	28.7	18.4	58	5	26.6	20.5	159	17
September	85	29.4	19.3	77	6	27.0	20.9	184	27
October	98	30.2	20.4	103	9	27.8	21.7	234	19
November	143	30.9	21.5	138	11	28.8	22.5	264	19
December	186	31.4	22.1	159	13	29.8	23.2	263	21
Total	1,868			1,809				3,041	

Source: Adapted from Fiji Meterological Service records.

For comparative purposes, the Cardwell to Innisfail region of Queensland has broadly similar temperature and rainfall regimes:

- The climate page for Innisfail suggests 3547 mm/y (although there is a dry winter) and much closer to Suva than Nadi in winter temperatures. http://www.bom.gov.au/climate/averages/tables/cw_032025.shtml
- The climate page for Cardwell suggests 2111 mm/y, which is closer to Nadi at, but 4 to 5 degrees cooler in the winter. http://www.bom.gov.au/climate/averages/tables/cw_032004.shtml

Soils and vegetation

Tropical Dry Forest once occupied about one-third of the land area of Fiji. Much of this area has been burned often enough such that it now supports open grassland (often mission grass) and talasiqa savanna.

Information on soils is available at Maps - Soils of Fiji (landcareresearch.co.nz). The soils in the study area are typically sallow, and depleted by fire and erosion. Various parent materials are reported including calcareous, sandstones, marlss tuffs, mixed basic, intermediate, and acidic in situ rocks, and marine limestone and elevated reef rock.

Proposed engagement with you, the expert

An early objective is to review literature and liaise with experts prior to developing a paper summarising technical information on the suitability of indigenous and exotic tree species for silvopastoral systems within the study area. Information will be collected on:

1. individual tree species which appear suited for sloping land silvopastoral systems;
2. species selection criteria upon which to evaluate tree species suitability for silvopastoral systems; and
3. suitable combinations of trees and livestock in silvopastoral systems.

I am seeking technical information from several experts, including:

- Marika Tuiwawa
- Sanjana Lal
- Sairusi Bulai

- Tevita Bulai
- Maika Tabukovu
- Vinesh Prasad
- Solomoni Nagaunavou
- Isaac Rounds
- Lex Thomson
- Deborah Sue
- David Lee
- Kevin Glencross
- Tony Page
- Steven Walker
- Fiji Pine Representative
- Fiji Hardwood Representative

I acknowledge that this is not an exhaustive list, and would appreciate your thoughts on other experts who could provide valuable to contributions to this project. I would be grateful if you could provide me with their contact details.

I would appreciate you responding to this email to let me know if you would like to participate and provide your expert knowledge. If so, please also provide suitable dates and times between now and the end of January 2022 when I could zoom or phone call you to discuss the project in more detail.

I look forward to discussing this project with you.

Robert Harrison
School of Agriculture and Food Sciences
The University of Queensland
St Lucia QLD 4072 Australia

Phone: +61 438 208 342

11.4.4 Second email to tree species experts

Thank you for responding to my request for your input on ACIAR project ADP/2016/147 – Improving Agroforestry Policy for Sloping Land in Fiji.

The following steps outline my proposed engagement with you.

Step 1. Inventory of potentially suitable tree species

Fiji has a long history of agroforestry and tree planting programs. Various lists of priority tree species for conservation and planting have been proposed under these programs.

An attempt has been made to identify tree species that are currently promoted in tree planting programs, or potentially suitable for forestry in Fiji. This list has been developed from a broad literature review, Government and NGO websites and from information provided to the project team during project field trips (including previous ACIAR project ADP/2014/013, ‘Promoting sustainable agriculture and agroforestry to replace unproductive land-use in Fiji and Vanuatu).

However, not all species identified from compiling this list are likely to be suitable for the study area.

It is proposed as an initial step to cut out the tree species that are clearly unsuitable to grow on the seasonally dry sloping lands of Fiji. To achieve this, **you are requested to** review the attached spreadsheet and select from the drop down tab, if, in your expert opinion, each tree species is capable of achieving a reasonable growth rate within the study area or not. An option to select "unsure" is also provided.

Step 2.

It is anticipated that step 1 will reduce the priority tree species list to a manageable number of species upon which to conduct a more detailed evaluation.

Draft species selection criteria, against which to evaluate tree species suitability for silvopastoral systems within the study area, have been developed. These criteria have been divided into groups dealing with biophysical requirements, markets, government regulations, and cultural, social and environmental factors. Under each criterion, several attributes will capture technical information relating to individual species performance.

Where technical information about better-known tree species is available, this will be prepopulated into a species attributes table.

It is proposed that I will conduct one-on-one interviews with you to collect this information.

As it is not expected that all tree species will be familiar, I will only be collecting more detailed information from you about those species you are comfortable to provide information about.

Step 3.

Responses from the interviews will be collated to provide expected performance ranges for each indicator for each species.

You will be invited to review this summary and recommend revisions.

Draft species selection criteria upon which to evaluate tree species suitability for silvopastoral systems within the Fiji study area

Criteria have been developed to guide species selection. Under each criterion a list of indicators (properties or attributes) is provided – these will not be relevant to all species in all settings.

Criterion 1) Species-specific Biophysical Characteristics and Requirements

- Climatic requirements
    - mean annual rainfall
    - distribution of annual rainfall
    - maximum and minimum temperatures
- Site and Soil requirements:
    - Performance on steep slopes
    - Performance on nutrient poor soil
    - Performance on shallow or rocky soil
- Fire tolerance
- Cyclone and wind resistance
- propagation ease:
    - Availability of improved provenance and/or genetics
    - Sexual propagation
    - Vegetative propagation
- Susceptibility to pest and diseases
- Plantation potential
- Growth rates and mean annual increment (MAI)
- Growth habit and form

- Harvest age

Criterion 2) Financial

- Cost of establishment and maintenance
  - Seed or seedling expense
  - Fast or slow early growth and weeding costs
  - Growth form and pruning costs
- Product reputation and utility
- Expected demand for products (e.g. timber mills)
- Expected farmgate prices ($/m^3 or $/product)
- Product reputation and utility
- Potential for financial return from early thinning – posts, fuelwood

Criterion 3) Silvopastoral systems potential

- Tree effects on pasture:
  - Tree growth form – surface or tap rooted,
  - Tree growth form – heavy or light shading
  - Allelopathy impacts on pasture
  - Nitrogen fixing
- Pasture impact on trees.
- Fodder potential
- Toxicity considerations
- Resistance to grazing, browsing and trampling

Criterion 4) Environmental considerations

- Invasiveness
- Endemism (Indigenous/exotic) Protection against erosion
- Conservation priority

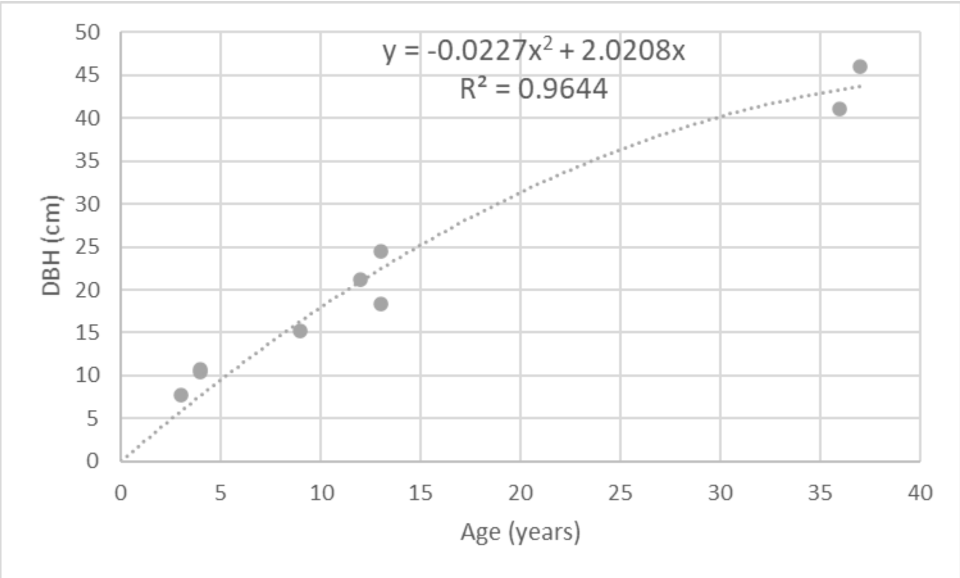
Criterion 5) Social considerations

- Significant cultural values such as ceremonial value
- Gender preferences
- Aesthetic and ornamental values
- Considered locally or nationally important

11.5 Appendix E: DBH and height models developed for spotted gum and vesi in Fiji

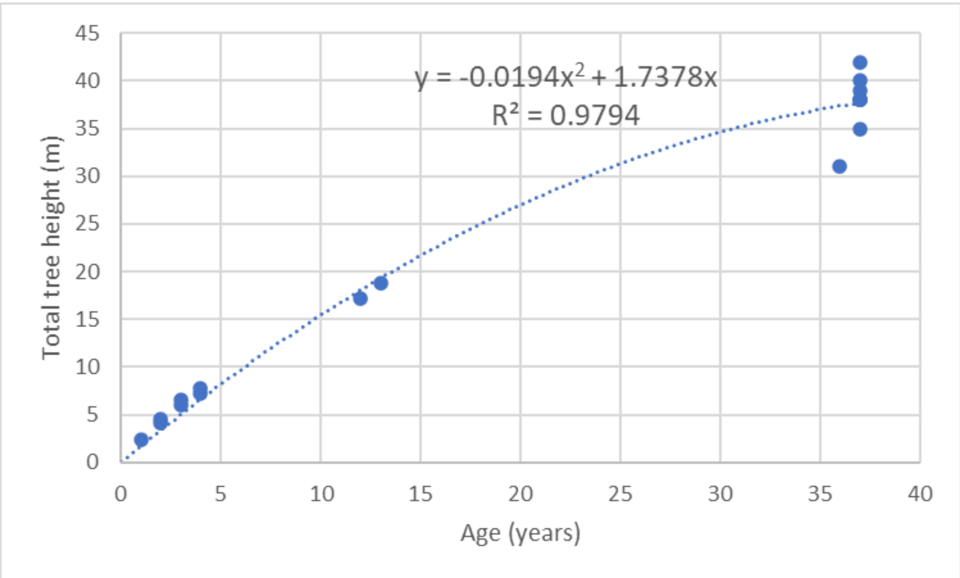
The spotted gum DBH and height models illustrated in Figures A1 and A2 were fitted to unpublished data provided by David Lee, University of the Sunshine Coast, for 36 to 37-year-old unmanaged trials in New Caledonia that were last measured in 2012-13.

Figure A1. DBH model for spotted gum



Source: Data used with permission from David Lee, University of the Sunshine Coast.

Figure A2. Total tree height model for spotted gum



Source: Data used with permission from David Lee, University of the Sunshine Coast.

A review of literature revealed no published growth models for vesi. Data was collated from several studies in Samoa, Papua New Guinea, Indonesia, Malaysia and the Philippines to which the DBH and total tree height functions illustrated in Figures A3 and A4 were fitted

(Langenberger *et al.*, 2005; Thaman *et al.*, 2006; Piskaut, 2007; Tong *et al.*, 2009; Schneider *et al.*, 2013).

Figure A3. DBH model for vesi

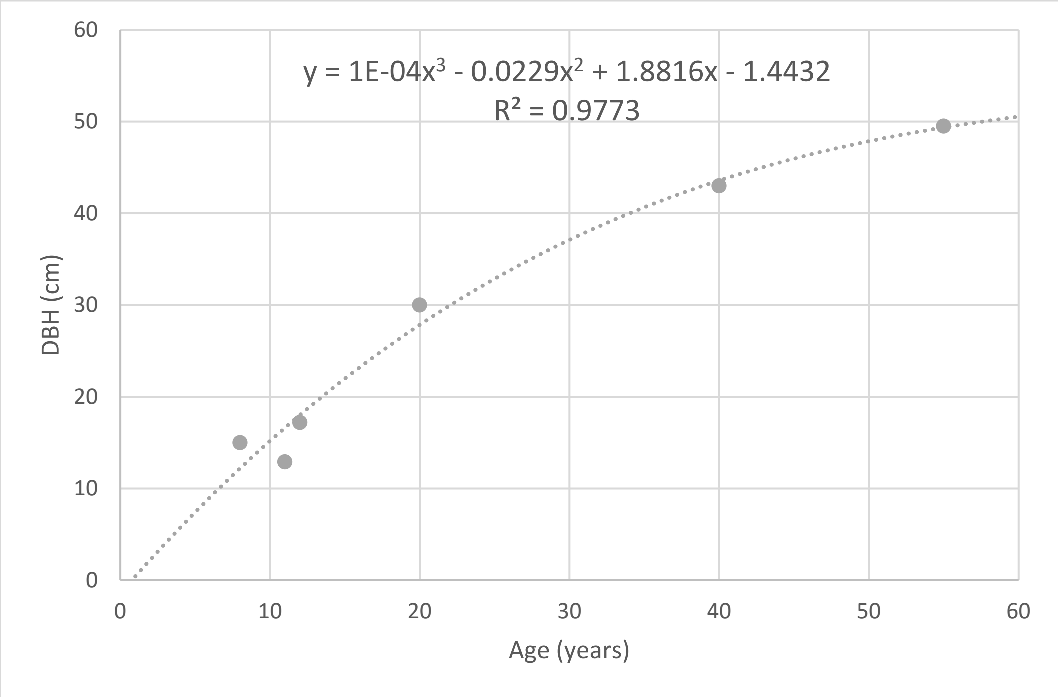
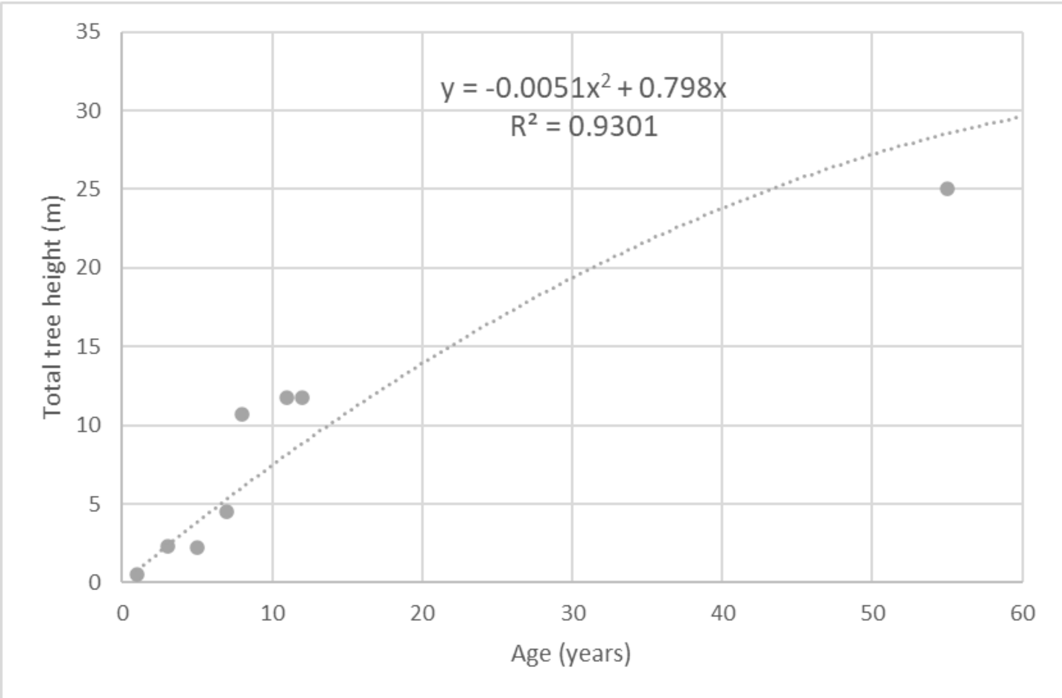


Figure A4. Total tree height model for vesi.



11.6 Appendix F: Labour requirements for silviculture in silvopastoral systems

Table F1 reports the timing and labour requirements for silviculture adopted in the analysis. The sandalwood management regime and labour requirements are based on Harrison and Karim (2016). Labour requirements for land preparation by weed slashing, tree planting, and weeding for all other tree species are based on Enterprise Challenge Fund (2013). However, weeding labour has been been reduced by 75 % to account for the use of a clearing saw (brush cutter) rather than hand tools. Pruning and non-commercial thinning labour requirements are described in the Table F1 notes, which were be multiplied by the number of stems treated (as reported in Table 3) to estimate the labour requirements in Table F1.

Table F1. Year (*t*) and labour requirements (LH_{at}) for each silvicultural activity, *a*

Activity (*a*)	Year (*t*) of activity and labour requirement (LH_{at}) by silvopastoral system									
	Vesi and pine		Teak		Pine		Spotted gum		Sandalwood [1]	
	Year	Labour (hours/ha)	Year	Labour (hours/ha)	Year	Labour (hours/ha)	Year	Labour (hours/ha)	Year	Labour (hours/ha)
Land prep. & plant	0	37.0	0	36.2	0	27.1	0	21.7	Sandalwood and stylo: 0 Leucaena: EF 0, No EF 4	27.5 58.8
Infilling [3]	1	1.3	1	1.3	1	1	1	0.8	Sandalwood: 1 Leucaena: 5	0.8 2.3
Weeding	0 1 to 3	5.2 20.8	0 1 to 3	4.8 19.0	0 1 to 3	3.6 14.3	0 1 to 3	2.9 11.4	EF: 0, 1. Between sandalwood rows 2 to 9 No EF: 0 1 to 2 3 to 4 5 to 9	10.6; 53.0 20.4 3.3 20.4 16.3 49.0
Non-com. Thinning [3]	Pine: 4 Vesi: 6	18.2 20.3	4	46.7	4	25	5	20.0	na	
Pruning [3]	Pine: 4 Vesi: 6, 15	21.2 11.7 15.0	5 8	23.3 18	5	29.2	5 10	23.3 18.0	Sandalwood EF and No EF: 1 to 4 Leucaena EF: n.a. Leucaena No EF: 5 to 9 [2]	6.9; 13.7; 17.1; 34.3. 38.1
Com.thin [4]	na		12		na		15		na	
Clearfall [4]	Pine: 15 Vesi: 40		25		20		30		Sandalwood: 26 Leucaena: n.a.	987.4
Total labour hours over the rotation		192.3		187.4		128.7		121.0		EF 1441.5 No EF 1660.7

Notes: 1. EF refers to the sandalwood system with electric fences. No EF refers to the sandalwood system without electric fences.
2. Before livestock are introduced to the sandalwood without EF system, the leucaena need to be lopped annually to about 1.5 m tall to promote bushy habit.
3. All scenarios except sandalwood: 5% of trees replanted at infilling; non-commercial thinning 6 minutes per tree; first and second prune 7 min and 9 min per tree.
3. For tree crops, commercial thinning and clearfall harvesting is assumed to be performed by a contractor and the landholder is paid a stumpage price. However, sandalwood is assumed to be harvested by the farmer, requiring six hours per tree (Harrison and Karim, 2016).

11.7 Appendix G: Forage establishment costs (FEC_{ft}) and dry matter production (DM_{ft}) for topical pasture, leucaena and stylo

11.7.1 Tropical pasture

The analysis assumes existing, unimproved tropical pasture is grazed by cattle, and forage establishment costs are zero. A review of published literature of Fijis pasture productivity and livestock carrying capacity relevant to the study area revealed limited information that could be used in modelling pasture or livestock productivity to inform a financial analysis of silvopastoral systems. In the absence of usable data from Fiji, estimates of livestock carrying capacities for this project have been informed by tools developed for Queensland grazing land management.

The GRASP pasture growth model is a soil-water, pasture-growth model developed for northern Australia and rangeland pastures (McKeon *et al.*, 2000) (Rickert *et al.*, 2000) and is considered adequate to represent native pasture growth in a wide range of systems (Zhang *et al.*, 2021) and has been used to assess carrying capacities (Whish, 2012). In this study, the GRASP pasture growth model was applied to estimate the effect of tree growth (increasing tree basal area) on pasture growth.

Rainfall in Fiji's seasonally dry sloping lands varies from 1500-2250 mm per year, but is strongly seasonal, with most rain falling during the December to April 'summer', while dry conditions prevail during the cooler remainder of the year. Average rainfall and temperature statistics are reported for Nadi in Table 1, and have been adopted to represent the study area. Only the month of July has an average rainfall less than 50 mm. The Cardwell to Innisfail region of Queensland has broadly similar temperature and rainfall regimes Pasture modelling simulations were undertaken using the Cedar GRASP version 2.1.01 (March 2020) from 129 years (1891-2020) of data for the MW06 Eucalypt hills and ranges Mackay Whitsunday land type for 20 levels of tree basal area (0 to 37 m^2/ha) using interpolated SILO climate data (https://www.longpaddock.qld.gov.au/silo/), for latitude 18.65 and longitude 145.85. Annual pasture growth has been simulated from 1st April to 31 March, and these estimates are plotted in Figure G1, along with a line of best fit that has been used to simulate annual pasture production for any tree basal area. In the tropical pasture only system, pasture production is modelled as 2662 kg DM/ha/y (basal area = 0).

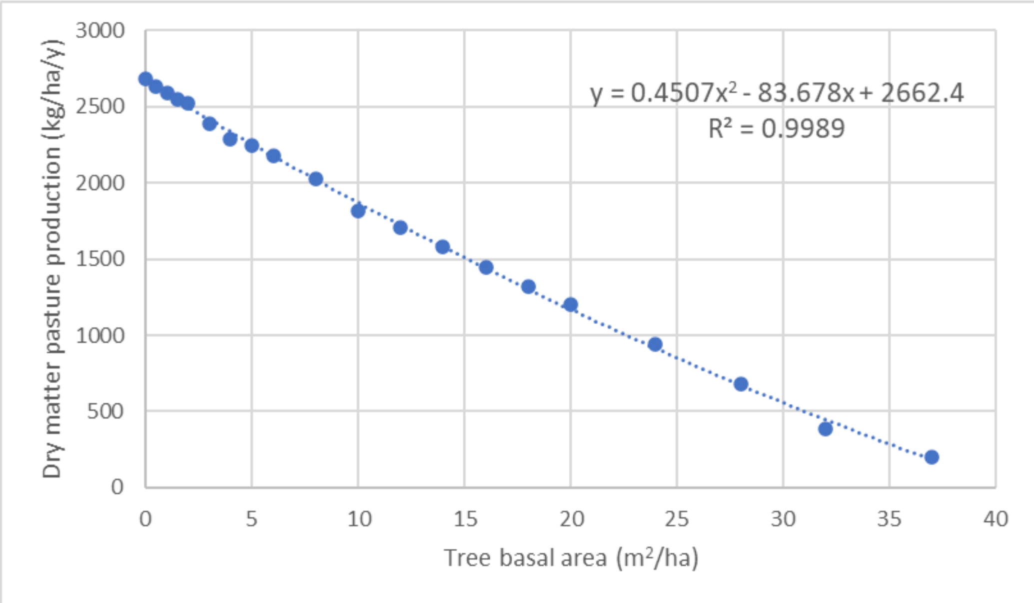
The GRASP model has been developed with data from Australian sclerophyll forests dominated by open-crowned *Eucalyptus* and *Corymbia* trees. The GRASP model is assumed to adequately represent the impact of spotted gum and sandalwood on pasture production. It is assumed that that for any particular tree size, the competitive effect on pasture by shading of pine, vesi and teak is 25 %, 50 % and 100% more than for spotted gum. This effect has been accommodated within the model by multiplying the basal areas of these systems by 1.25, 1.5 and 2.0 for the purposes of estimating the level of pasture production in any particular year.

11.7.2 Leucaena

Meat and Livestock Australia recommended that 35 % to 40 % of cattle diet be leucaena to maximise liveweight gain, and there is limited liveweight gain benefit associated with higher proportions of leucaena in the cattle diet. Under Australian conditions and management regimes, 40 % leucaena diet results in liveweight gain of about 1 kg/animal/day (Dalzell *et al.*, 2006). The analysis for Fiji assumes 0.5 kg/animal/day.

In this study, leucaena is relevant only to the leucaena improved tropical pasture scenario, the spotted gum and leucaena improved tropical pasture silvopasture system and the sandalwood systems. Leucaena utilisation as a Sandalwood host has been reported in Page *et al.* (2018) and Rome *et al.* (2020). Considerable plant breeding has occurred with leucaena around the development of psyllid-resistant varieties and, more recently, efforts to produce sterile varieties (Real *et al.*, 2019). The analyses performed in this assessment assume planting of sterile seedlings that are not yet commercially available. It would be a question for Fijian authorities as to whether fertile leucaena would be permitted for establishment within the study area, as leucaena can become a weed.

Figure G1. Projected tropical pasture production per annum as a function of tree basal area



Source: Data provided by Giselle Whish, Queensland Department of Agriculture and Fisheries, and the line of best fit was fitted by the authors.

In Australia, leucaena is typically established from seed in mechanically tilled rows (Dalzell *et al.*, 2006). This allows dense sowing of seed and individual leucaena plants are kept small by competition and grazing. It is assumed that leucaena seedlings will be planted in Fiji at relatively wide spacing, because establishment from seed would require intensive land preparation that is unlikely to be technically feasible throughout most of the study area. Research from Thailand demonstrated that the yield of edible leaf and small branches is similar for a range of leucaena planting densities. For example, in year 4, the 1 m x 0.25 m plot produced 6200 kg DM/ha and the 2 m x 1 m plot produced 5800 kg DM/ha (Chotchutima *et al.*, 2013). However, less dense plantings will require more active management to control the height of leucaena if cattle are not introduced in year 2.

A wide range of dry matter (DM) yields have been reported, ranging from 2 to 40 tonnes of DM/ha/year depending on climate, rainfall and leucaena variety and management regime (Guevarra *et al.*, 1978; Othman *et al.*, 1985; Garcia *et al.*, 1996; Mullen *et al.*, 2003; Aminah and Wong, 2004)[8]. Leucaena dry matter production (DM_{ft}) is often reported in terms of rainfall use efficiency (RUE), quantified as kg DM/ha/mm rainfall. At a high rainfall site at Redland Bay, Queensland, with leucaena planted at various densities and where pasture competition was controlled, the RUE ranged from 4 to 16 kg DM/ha/mm (Dalzell *et al.*, 2006). At Rolleston in central Queensland with intensively competitive buffel grass and a

[8] https://www.tropicalforages.info/text/entities/leucaena_spp._hybrids.htm

moderate annual rainfall of 600 mm, RUE was 2.2 kg DM/ha/mm with double-rows of leucaena planted 6 m apart (Dalzell *et al.*, 2006).

In this study, an RUE of 2.2 kg DM/ha/mm has been adopted, which assumes 6 m inter-rows between double-rows of leucaena 75 cm apart, and spacing between leucaena within the rows of 2 m. Therefore, based on annual rainfall of 1750 mm, leucaena is assumed to produce about 3850 kg DM/ha/y in the study area. In the leucaena improved tropical pasture scenario and the spotted gum and leucaena improved tropical pasture silvopasture system, sufficient leucaena is planted within the property to achieve the recommended 40 % of livestock diet. The average distance between the leucaena rows in the sandalwood systems modelled is 8 m, which results in 25 % less plants and lower yield per hectare (2888 kg DM/ha/y).

The leucaena adds nitrogen to the soil, but competes with the tropical pasture for sunlight, moisture and other nutrients. The leucaena double rows are assumed to completely shade-out 1.75 m wide strips of pasture (the 0.75 m inter-row, plus 0.5 m on the outside of each row). In a standard system with 6 m of pasture between leucaena double-rows, the leucaena shades out 2917 m^2/ha in each hectare that leucaean is planted. This is accommodated within the analysis as a decrease in tropical pasture of 29 % in the hectares where leucaena is planted. In the sandalwood systems where the average spacing between leucaena double-rows is 8 m, the leucaena reduces pasture production by 20 %.

The establishment costs for leucaena (FEC_{ft}) are described in the tree modelling section for sandalwood systems. For sandalwood systems, the leucaena is treated as a long-term host for sandalwood with grazing co-benefits, and FEC_{ft} is zero. For the leucaena improved tropical pasture scenario, and the spotted gum and leucaena improved tropical pasture silvopasture system, FEC_{ft} is as reported for leucaena in the sandalwood systems.

11.7.3 Stylo

Stylosanthes spp. (stylo) production is only relevant to the sandalwood systems, where this species performs the role of an intermediate host, as well as providing fodder for livestock. According to Page *et al.* (2018), stylo is a forage legume that may be considered a sandalwood host in a controlled grazing system. A number of *Stylosanthes* species have been developed that are suited to long-term topical pasture systems. The choice of stylo will depend on site-based factors; however, using a stylo mix provides greater certainty of including a stylo that will persist over the long term within the silvopastoral system.

Stylo can produce between 2000 kg/ha/y and 7000 kg/ha/y of dry matter[9]. Since the stylo will be parasitised by the sandalwood, and be competing with sandalwood for nutrients, light and water, the analysis assumed production of 2000 kg/ha/y. The stylo is sown in the 4 m inter-row between sandalwood rows, which represents 2286 m^2/ha in the modelled system. Consequently, the stylo is estimated to generate 457 kg/ha/y of dry matter for livestock.

The establishment costs for stylo are captured as part of the sandalwood system establishment costs, since the stylo is planted as an intermediate host (witht fodder production co-benefits).

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[9] https://www.tropicalforages.info/text/entities/stylosanthes_scabra.htm; https://www.selectedseeds.com.au/; https://barenbrug.com.au/forage-pasture/tropical-2/tropical-legumes.

11.8 Appendix H: Sensitivity analyses for modelled systems

This appendix reports the sensitivity of LEV of modelled systems to:

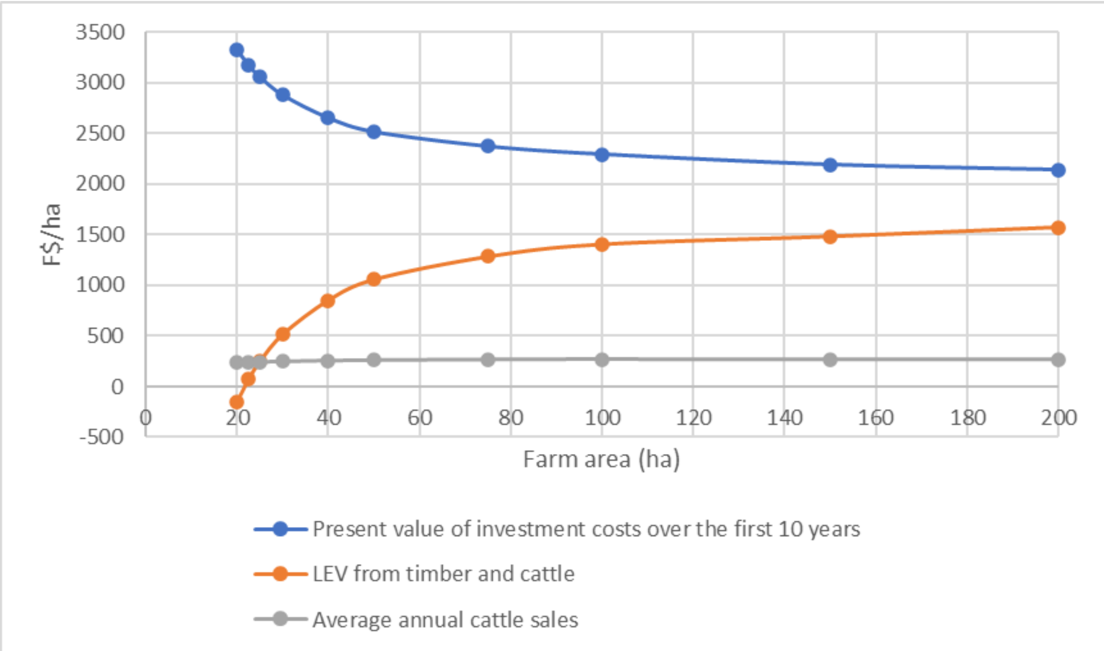
1. farm size;
2. sandalwood growth rate and price;
3. timber stumpage prices for non-sandalwood silvopastoral systems;
4. tree growth rates for non-sandalwood silvopastoral systems;
5. farmgate liveweight cattle prices; and
6. the discount rate.

11.8.1 Sensitivity of financial performance of silvopastoral systems to farm size

The case study analysis has focussed on a 200 ha lease area for most silvopastoral systems in a nation where 96.6 % of farms are less than or equal to 10 ha in area. However, it is important to reiterate that the study area is not classified as agricultural land in Fiji due to steep slopes and poor soils. Nevertheless, a sensitivity analysis has been performed to identify the minimum viable silvopastoral farm size for the spotted gum system.

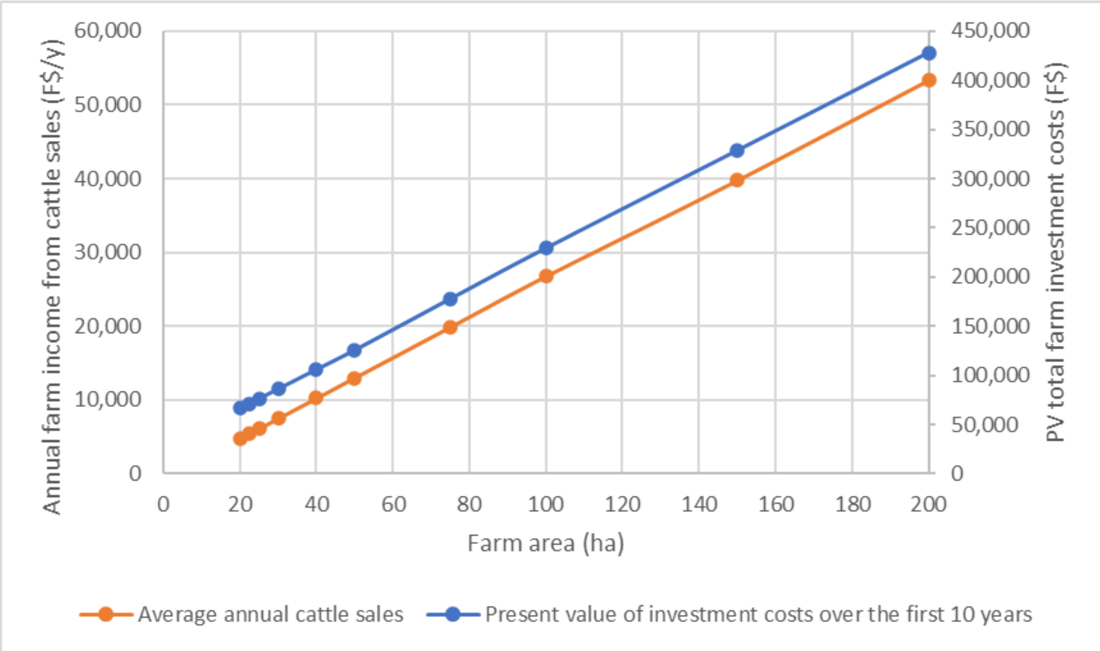
Figure H1 indicates the present value of investment costs, annual cattle sales and LEV per hectare as a function of farm size. Investment costs decline as fixed costs are spread over greater area. Annual cattle sales per hectare increase slowly from F$230/ha on a 20 ha farm to F$269/ha on a 200 ha farm. LEV from timber and cattle components of the silvopastoral system rises with farm scale. One way to determine a minimum viable farm size is to set LEV equal to zero. On that basis, the minimum viable farm size is about 22.5 ha if there is no need for water infrastructure and other capital costs not explicitly accounted for in the analysis. However, if water infrastructure is required at a cost F$500/ha, then the minimum viable farm size rises to 30 ha.

Figure H1. LEV, present value of investment costs and average annual cattle sales per hectare as a function of farm area for spotted gum silvopasture



Importantly, the LEV-determined minimum viable farm size does not account for the temporal variability of farm income, with the zero LEV largely dependent on spotted gum income from thinning in year 15 and the clearfall in year 30. Therefore, the level of non-silvopastoral system income available to supplement income from cattle sales to pay for silvopastoral system expenses is a key assumption when determining minimum viable farm size. Non-silvopastoral system income could include off-farm income and on-farm income from agricultural land (e.g. cane) elsewhere within the lease. Figure H2 suggests small silvopastoral farms would require substantial levels of off-farm income to cover annual farm expenses. For example, a 40 ha silvopastoral system is projected to generate F$10,240/y in cattle sales, but this is barely above the annual income for a full-time worker on Fiji's minimum wage (F$4/h). If the silvopastoral system needs to generate income to cover all farm management costs until the trees in the silvopastoral system are harvested, then the minimum viable farm size will need to be much larger than the farm size that generates a zero LEV. A 75 ha farm appears to be the minimum farm size that could generate sufficient income from cattle to cover farm management costs, including providing an annual income for the leaseholder. Given variability in markets and growing conditions over time, a more sustainable minimum viable farm size is likely to be about 100 ha.

Figure H2. Total present value of investment costs and average annual cattle sales for the whole farm as a function of farm area for spotted gum silvopasture



Finally, the decision about farm size will also be influenced by the availability of funds for investment. A 100 ha farm would require a present value of investment over the first 10 years of F$229,500, excluding any necessary water infrastructure. Therefore, establishment of silvopastoral systems in the study area will likely require a combination of long-term, low-interest rate loans, and material, financial and extension support from foreign donors, the Fijian government and non-government organisations.

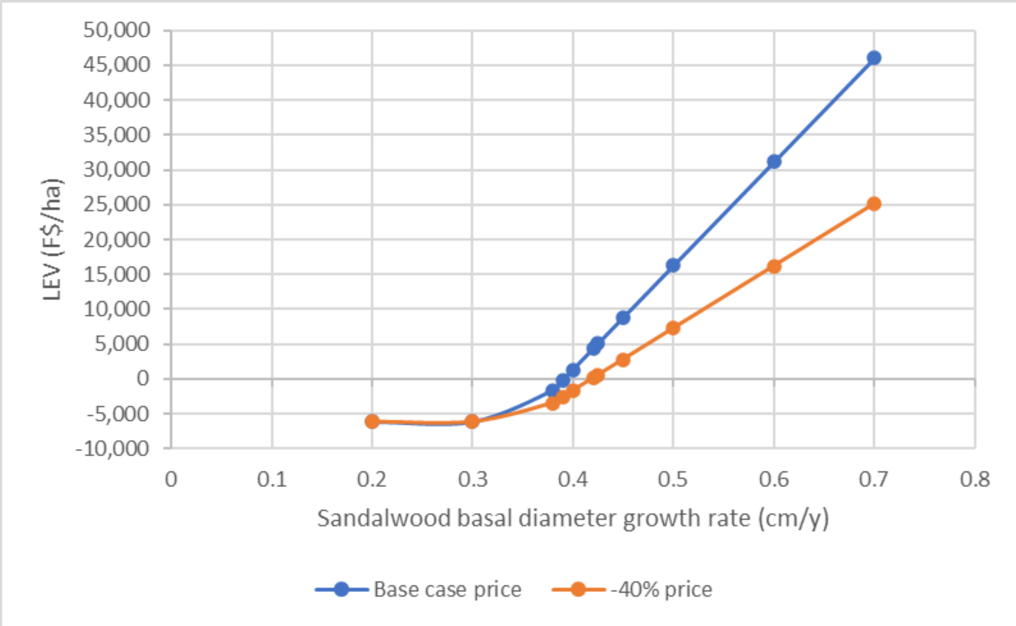
11.8.2 Sensitivity of financial performance of sandalwood systems to the sandalwood growth rate and price

The LEV of the sandalwood silvopastoral system is particularly sensitive to the growth rate of sandalwood, but not price. As indicated in Figure H3 for the system without the electric fence[10], a zero LEV is achieved with the base case sandalwood price at a basal diameter growth rate of 0.39 cm/y, which is a 44 % reduction in the rate of growth assumed in the base case (0.7 cm/y). At a basal diameter growth rate of 0.42 cm/y, the sandalwood system was projected to generate a higher LEV than any other modelled system (F$4326/ha) with

[10] *Sensitivity of LEV is very similar for the system with the electric fence. The LEVs are just a little smaller.*

all other parameters at their base case levels. If sandalwood prices have been overestimated by 40 %, and are better represented by F$45/kg, then LEV of the sandalwood system is zero at a basal diameter growth rate of 0.42 cm/y. The viability of the sandalwood system is completely dependent on the rate of growth achieved by sandalwood in these landscapes. There is no empirical evidence of sandalwood growth rates in these landscapes. Trials are necessary to ensure adequate growth rates in the study area landscape.

Figure H3. Sensitivity of LEV of the sandalwood without electric fence silvopastoral system to the average annual growth rate of sandalwood and sandalwood price



11.8.3 Sensitivity of financial performance of non-sandalwood silvopastoral systems to timber stumpage prices

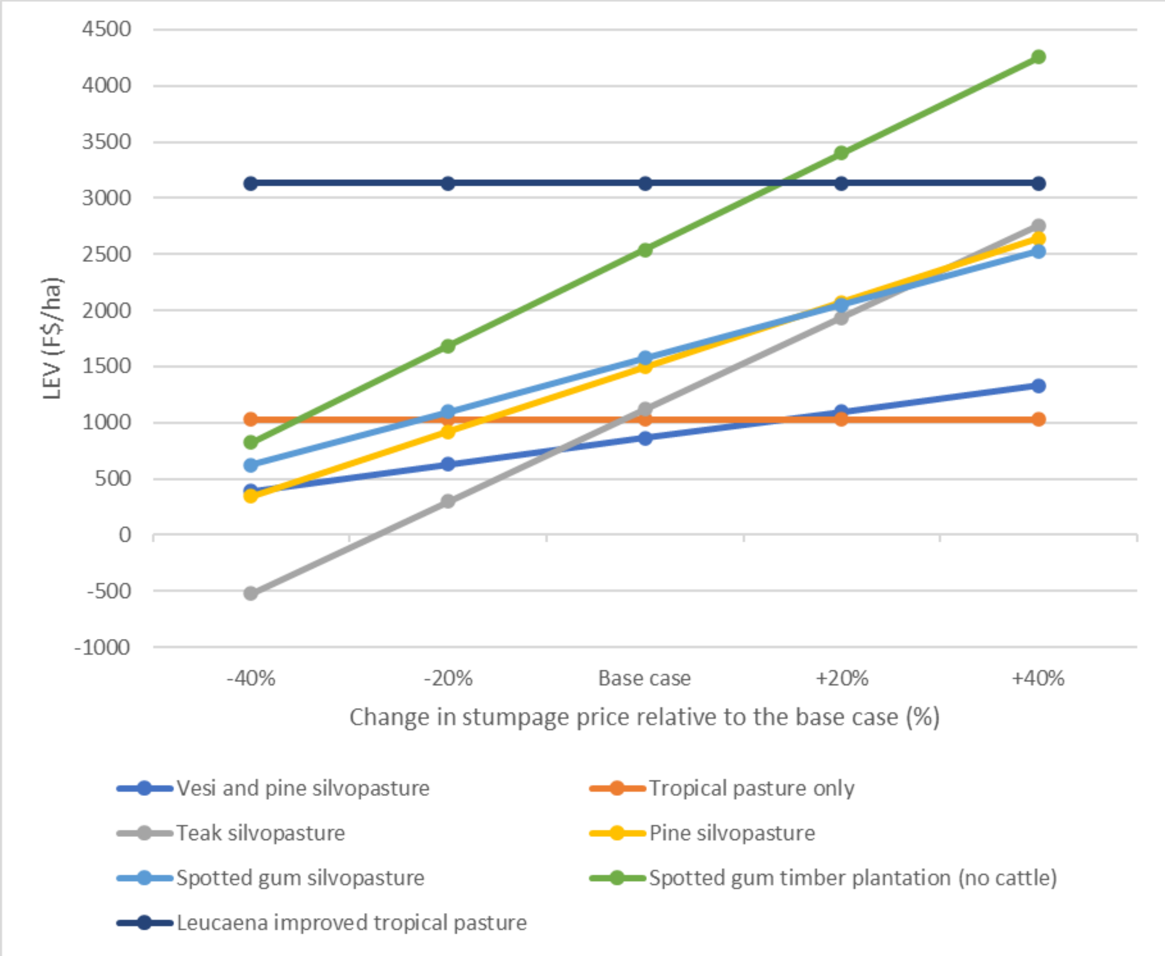
Figure H4 illustrates the sensitivity of LEV to timber stumpage prices for all species except sandalwood. All silvopastoral systems except teak are financially viable even if stumpage prices have been overestimated by 40 %. So most silvopastoral systems are robust against changes in stumpage prices.

Vesi silvopastoral systems are least sensitive to stumpage prices because this species has the longest rotation and relatively low impact of the trees on grazing revenues over much of the rotation, such that grazing revenues are quite important in this system. Even if vesi stumpage prices have been underestimated by 40 %, pine and spotted gum silvopastoral systems still offer better returns at their base case stumpage prices.

In contrast to vesi, teak LEV is highly sensitive to stumpage prices, because of the comparatively short rotation and the fact that teak shades out grass production from an early age, both of which increases the relative importance of stumpage prices in the teak silvopastoral system. If teak stumpage prices have been underestimated by 20 %, then the teak silvopastoral system would outperform all other silvopastoral systems at their base case stumpage prices. Teak is the only timber species where a thorough investigation into stumpage prices is warranted, as they have the potential to either totally ‘make or break’ this silvopastoral system.

Spotted gum and pine LEVs are moderately sensitive to stumpage prices and, as long as stumpage prices have not been overestimated by more than about 20 %, silvopastoral systems with either of these species generate a higher LEV than the tropical pasture only system. The spotted gum plantation (no cattle) scenario outperforms all silvopastoral systems at all stumpage price levels, and is projected to outperform the leucaena improved tropical pasture system at high stumpage prices.

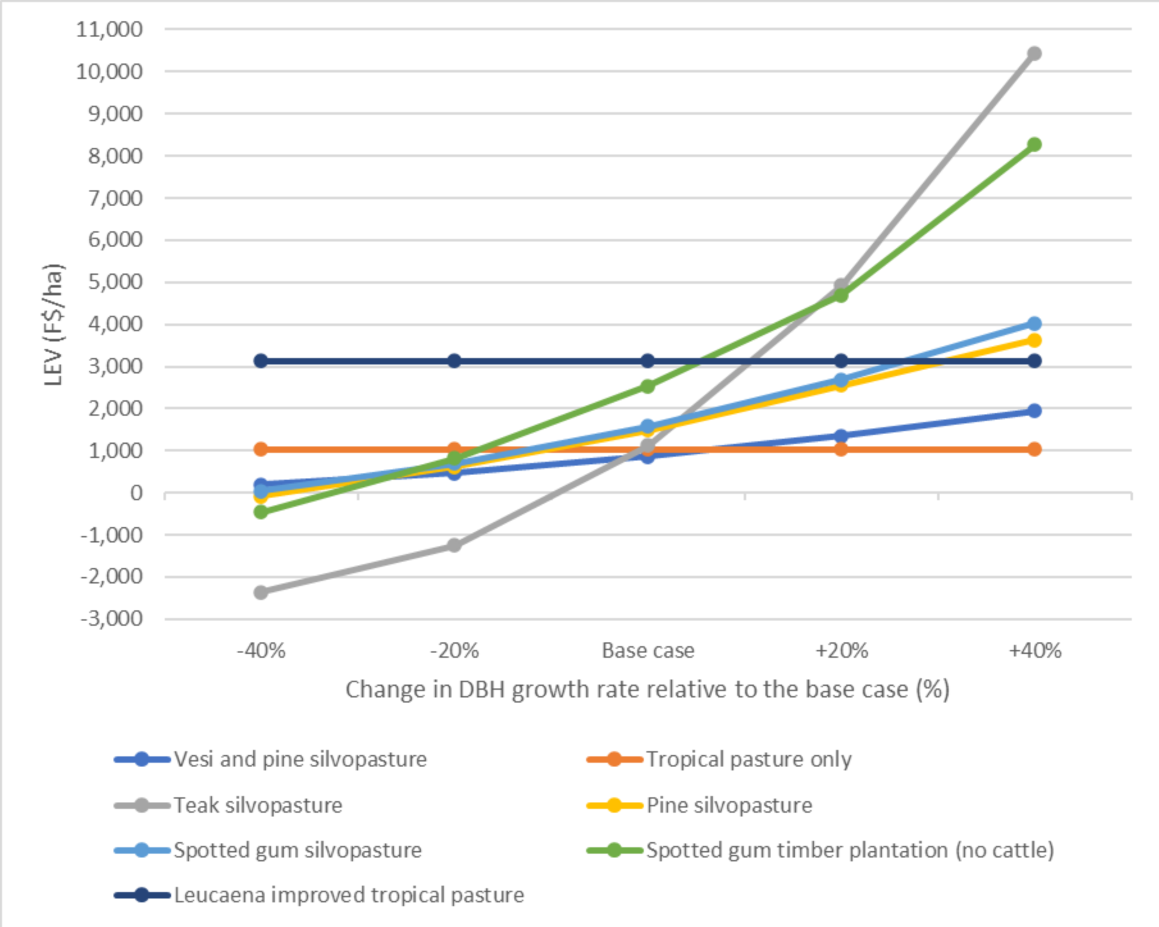
Figure H4. Sensitivity of LEV of modelled systems (except sandalwood) to stumpage prices



11.8.4 Sensitivity of financial performance of non-sandalwood silvopastoral systems to tree growth rates

Figure H5 reports the sensitivity of LEV to changes in DBH growth rate. These sensitivity analyses do account for improved pasture and cattle production if the trees grow slower (lower basal area in any given time period), and reduced pasture and cattle production over time if the trees grow faster (higher basal area in any given time period).

Figure H5. Sensitivity of LEV of non-sandalwood silvopastoral systems to changes in DBH growth rate



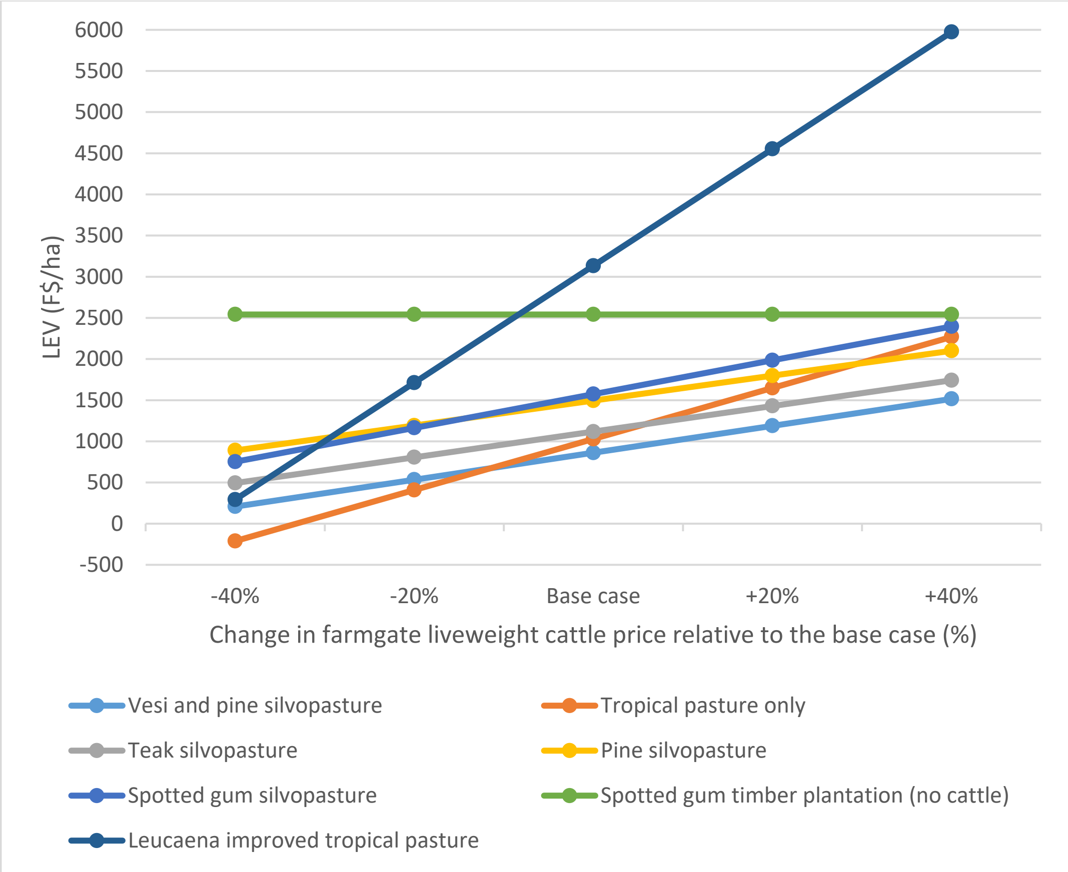
Several systems have been projected to out-perform leucaena improved tropical pasture if base case growth rates under-estimate achievable growth rates by 20 % to 40 %. Spotted gum and vesi systems always generate positive LEVs, even if tree growth rates have been overestimated by 40%. These two systems generate the most diversified mix of farm revenues, with grazing revenues being relatively more important in these two systems than the other silvopastoral systems, which buffered these systems better against poor tree performance. Pine and spotted gum plantations (no grazing) continue to generate positive LEVs with a 20 % decline in growth rates, but have negative LEVs with a 40 % decline in growth rates. The financial performance of teak silvopasture is highly sensitive to tree growth rate. At high growth rates, teak silvopasture is the best non-sandalwood system. At low growth rates, it is the worst performing system!

If growth rates in the base case overestimate achievable growth rates by 20 %, then all non-sandalwood tree systems perform worse than tropical pasture only. Decisions about whether silvopastoral systems are financially optimal on these Fijian landscapes and which species to plant will be greatly assisted by establishing long-term trial plots.

11.8.5 Sensitivity of financial performance of silvopastoral systems to farmgate liveweight cattle prices.

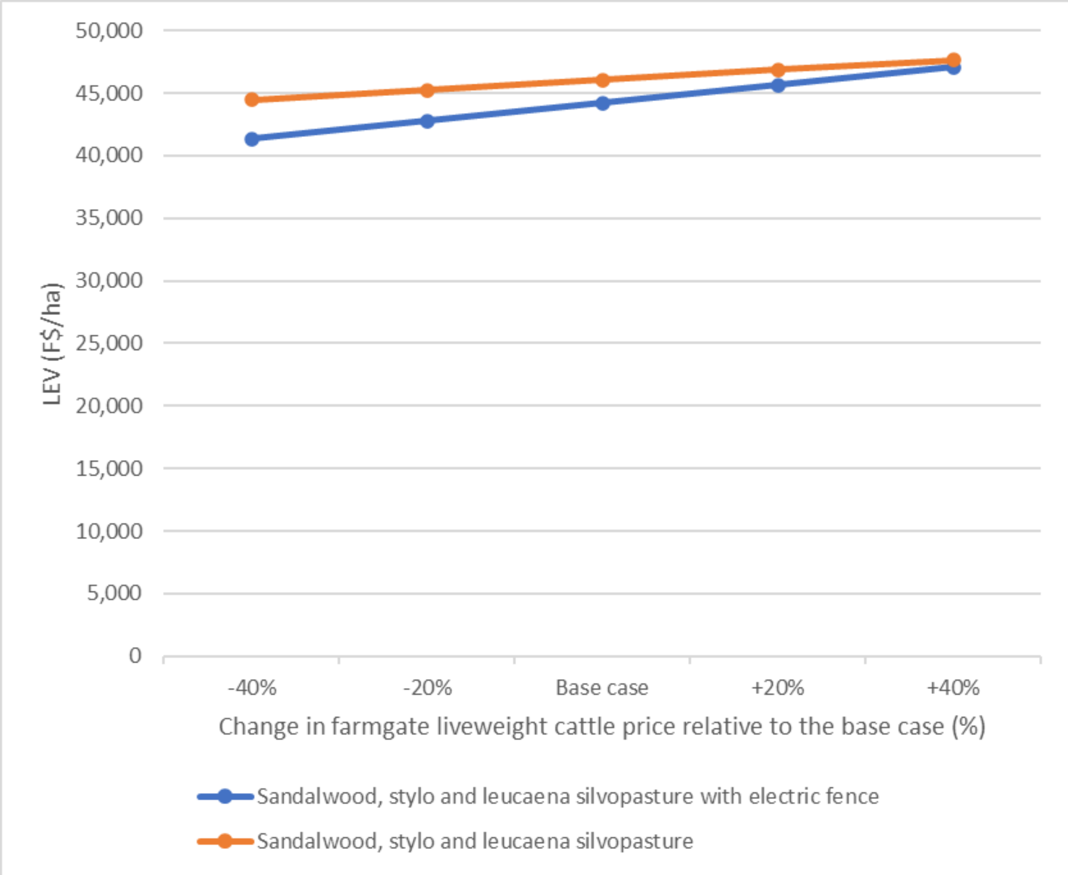
Figure H6 reports the sensitivity of LEV for non-sandalwood systems to the farmgate liveweight cattle price. Figure H7 indicates that the sandalwood systems are not sensitive to the farmgate liveweight cattle price. As expected, the tropical pasture only and leucaena-improved tropical pasture systems are most sensitive to changes in cattle prices, since there is no diversification of income with tree crops. If cattle prices fall about 30 % from the base case, then spotted gum and pine silvopasture systems will outperform leucaena improved tropical pasture systems. Cattle prices have been volatile historically, and have risen 140 % in Fiji from 2012 to 2022. This suggests further research to better project long-term farmgate liveweight cattle prices in Fiji is warranted.

Figure H6. Sensitivity of non-sandalwood system LEV to changes in farmgate liveweight cattle prices



The spotted gum system is shown to be the silvopastoral system that is most sensitive to changes in cattle prices. This is due to the relatively high cattle carrying capacity under spotted gum. Even at high (+40 %) cattle prices, spotted gum silvopasture continues to generate a higher LEV than the tropical pasture only system.

Figure H7. Sensitivity of sandalwood system LEV to changes in farmgate liveweight cattle prices



Note: The sandalwood with electric fence scenario is more sensitive to cattle prices because grazing can commence in year two with the electric fence, compared to year 10 without the electric fence.

11.8.6 Sensitivity of financial performance of silvopastoral systems to the discount rate

The sensitivity of LEV for each system to the discount rate is reported in Figures H8 and H9. Due to the long payback period for tree crops, all silvopastoral systems are much more sensitive to the discount rate than the tropical pasture only and leucaena improved tropical pasture systems, with higher discount rates disadvantaging silvopasture systems relative to grazing only systems. Lower discount rates favour silvopasture and plantation forestry. For example, because of its long rotation, the vesi silvopastoral system is particularly favoured by low discount rates; at 4 %, vesi provides a comparable return to spotted gum silvopasture and leucaena improved tropical pastures. With the exception of sandalwood, the silvopastoral systems begin to return negative LEVs when the discount rate is between 10 % and 12 %. Sandalwood LEV is particularly sensitive to the discount rate, ranging from F$180,000/ha to negative at 16% for the system with the electric fence and 20 % for the system without the electric fence. Consequently, at a 20 % discount rate, the tropical pasture only system outperforms sandalwood because of the low investment costs of this system, although the LEV is negative. Tropical pasture only is the worst performing investment at discount rates less than 8 %.

Figure H8. Sensitivity of LEV of modelled systems (except sandalwood) to the discount rate

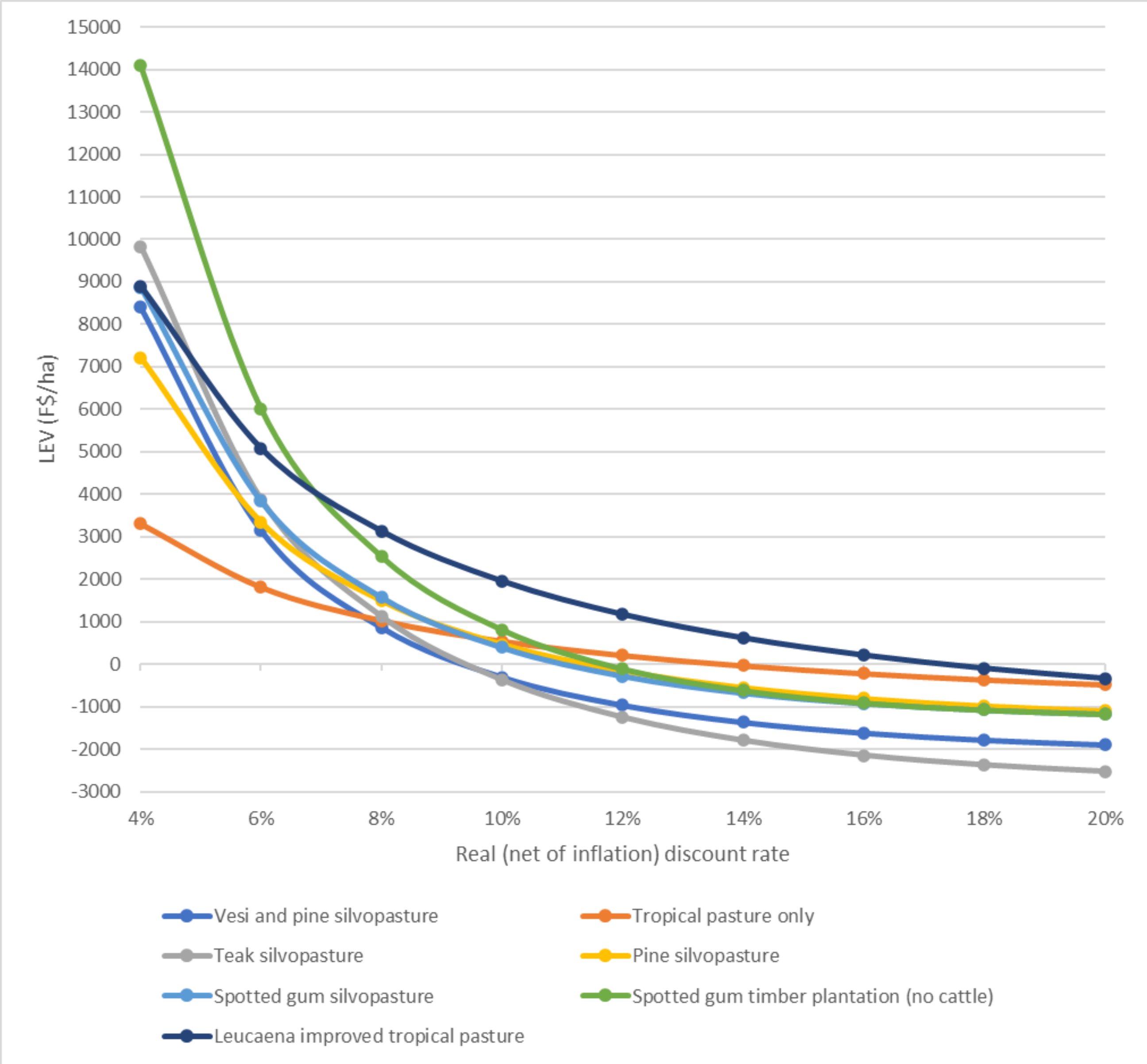


Figure H9. Sensitivity of LEV of the sandalwood systems to the discount rate