University of New England

Impacts of forage legumes on smallholder crop-livestock systems in West Timor, Indonesia

A dissertation submitted by

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I dedicate this thesis to my grandparents, John and Joan Gabb,

and to all other grandparents who support their grandchildren’s education.

Abstract

Smallholder crop-livestock systems are critical to future food security and meeting rapidly rising demand for livestock products. Yet, increasing competition for resources and high levels of soil degradation means farmers must produce more agricultural outputs without using more land, water or other inputs. Herbaceous forage legumes are one strategy for intensifying crop-livestock systems. However, current adoption levels are low and there is great uncertainty over the benefits, trade-offs and constraints of integrating forage legumes into farming systems at a farm and household level. Forage legume research has largely focused on agronomic performance and, consequently, the socio-cultural and economic factors which define the potential role of forage legumes in smallholder farming systems are poorly understood. Critically, little consideration has been given to the impact of gender roles on forage legume adoption and the distribution of impacts within a household. This thesis identifies potential opportunities for integrating forage legumes into smallholder crop-livestock systems in West Timor, Indonesia, and the benefits and trade-offs at a farm and household level.

The impact of forage legumes on farm production depends on the allocation of legume nitrogen (N) to crop and livestock enterprises. In Chapters 2 and 3, the impact of forage legume biomass management (retained vs. cut and removed) on inputs of fixed N, soil N and subsequent maize yield was assessed for an irrigated field experiment. While retaining shoot biomass contributed equivalent to 100-150 kg urea-N/ha and increased maize yield by 6-8 t/ha, there was little or no yield benefit when legume biomass was removed. The N fixation efficiencies (9-27 kg fixed-N/t shoot DM) and maize yield responses (5.8-7.9 t/ha higher yield compared to a maize control) were also double

what is commonly achieved under dryland systems, indicating effective soil N and water management and sufficient yield potential are required to realise meaningful production benefits. As large trade-offs exist between allocating legume N to crop or livestock enterprises, alternative management options, such as grazing or partial biomass removal, may be required to achieve dual soil N-fodder benefits.

Good agronomic practice is required to maximise the yield benefits of forage legumes. In Chapter 4, simulations for six case study sites in West Timor indicated that increases in maize yield of up 3.5 t/ha could be achieved if legume shoot biomass was retained, maize was planted at high densities (4-6 plants/m^2) and weed control was effective. Critically, in West Timor, plant available water rather than soil N constrained crop production in poor years. Thus, the largest and most consistent yield responses from forage legume production are likely to be achieved for years and sites with low soil N fertility and high rainfall.

Despite the yield benefits of green manuring legume biomass, farmers often favour allocating biomass to increasing livestock production, as it provides more substantial economic benefits. In Chapter 5, whole farm and participatory modelling quantified the production and economic impacts of forage legumes for six case study farms. When used as fodder, forage legumes can more than double farm income, although they must be integrated with staple crops or planted on unutilised land to achieve such substantial benefits. The marginal value of feed increased with herd size from 0.9-1.0 M Rp/t TLU^{-1} for smaller herds ($\leq$2 TLU) to 1.8-3.1 M Rp/t TLU^{-1} for larger herds (>2 TLU), indicating there were larger economic benefits for larger herds (TLU; Tropical Livestock Unit). Participatory scenario analysis indicated that livestock focused

farmers favoured larger areas of legumes than other farm types. This indicates that farmers with sufficient incentive, land, labour and capacity to invest are likely to benefit most from forage legumes.

While forage legumes can provide large economic benefits, the impacts of technologies are often unevenly distributed between men and women. In Chapter 6, participatory on-farm evaluation assessed the potential benefits and constraints of forage legume production for male and female farmers. Preferences reflected gender roles; women favoured integrating forage legumes with food crops to increase soil fertility and crop yield, while men favoured permanent stands as they provided the largest economic benefit. Labour was identified as the key constraint to adoption, with unequal distribution of household labour suggesting that forage legumes may increase women's labour requirements but maintain or decrease men's labour requirements. Thus, forage legume adoption requires labour saving options and more equitable distribution of benefits and labour inputs between men and women.

This research demonstrated that integrating forage legumes into smallholder crop-livestock farming systems can provide significant production and economic benefits. Yet, there are also large trade-offs associated with legume management, labour, land use and the inequitable distribution of household impacts. Further research is required to validate these potential impacts and how they may differ for a broader range of farmers and farming systems.

Certification Page

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

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__________________________________ 1/12/2017

Signature of candidate Date

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Conference presentations

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Gabb, S., Bell, L., Basuno, E., Prestwidge, D., Prior, J. (2016). Intensifying forage-livestock systems: tradeoffs between food security and income, *14th European Society of Agronomy Conference*, Edinburgh, Scotland

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Abbreviations

a.i.	Active ingredient
APSIM	Agricultural Production Systems simulator
ASL	Above sea level
C	Carbon
DAS	Days after sowing
DM	Dry matter
EC	Electrical conductivity
ENT	East Nusa Tenggara
IAT	Integrated Analysis Tool
LLR	Land:labour ratio
LW	Liveweight
%Ndfa	Proportion of plant nitrogen derived from atmospheric N_2
N	Nitrogen
$\delta^{15}N$	^{15}N abundance
NH_4^+	Ammonium
NO_3^-	Nitrate
NUE	Nitrogen use efficiency
P	Phosphorus
PAWC	Plant available water capacity
PCA	Principle component analysis
CA	Cluster analysis
Rp	Indonesian rupiah
S	Sulfur
s.e.	Standard error

SOC	Soil organic carbon
TLU	Tropical livestock unit
TTS	South Central Timor

1. General introduction

1.1. Global overview of the importance, adoption and impact of forage legumes

Crop-livestock systems are one of the main forms of agriculture in developing countries, currently producing almost half of the world's cereals, most of the staple crops consumed by the poor and the majority of animal products in the developing world (Herrero et al. 2009). Thus, these systems are critical to future food security as well as meeting rapidly rising demand for livestock products in developing countries, which is occurring in response to population and income growth, urbanization and changing dietary preferences (Delgado 2005). Although chicken and pig production will meet most of this demand, ruminant production is also forecast to increase substantially (Herrero et al. 2009). In such mixed crop-livestock systems, livestock can have large cultural and economic value (Dugue et al. 2004), while also acting as an investment, a risk mitigation strategy to buffer emergency expenses or low crop yields (Dercon 1998), as well as a source of manure (Rufino et al. 2007) and draft power (Herrero et al. 2010). However, feeding livestock will become increasingly difficult, with competition for biomass for fodder, food, fertiliser and fuel already high (Dixon et al. 2010). This is particularly important given rising competition for resources, including land, water and nutrients (Herrero et al. 2010), and the high levels of soil degradation in Asia and Africa (Lal 2004). Consequently, there is increasing external pressure for smallholder farmers to produce more agricultural output without using more resources. In some regions, including parts of Asia, the key to addressing these pressures will be to develop sustainable intensification methods that improve on-farm efficiency to produce more food without using additional resources (Herrero et a. 2010). Thus, options that raise productivity and resource use efficiency are key to intensifying crop-livestock systems and meeting increased global demand for grain and animal products.

One strategy for intensifying crop-livestock systems is the introduction of improved grass or legume forages (Bouwman et al. 2013; White et al. 2013). Of these forages, herbaceous type forage legumes and the associated nitrogen (N) fixation can produce high quality livestock fodder as well as increase soil fertility and subsequent crop productivity (Drinkwater et al. 1998; Peoples and Herridge 1990). This literature review will provide a global overview of the role of forage legumes in crop-livestock systems and their agronomic and socioeconomic performance before introducing more specific literature on the potential role of forage legumes in West Timor, Indonesia. Globally, forage legumes are primarily used as pasture, hay or cut and carry fodder for dairy and commercial meat production (Franzel et al. 2005; Shelton et al. 2005). This can increase livestock productivity by improving live weight gains, milk production, mortality levels and stocking rates (Peoples and Herridge 1990) while also producing hay (Guodao and Chakraborty 2005) – a salable commodity – and reducing cut and carry labour requirements (Connell et al. 2010). Although this indicates that forage legumes are predominantly used for livestock production, forage legumes can also increase grain yield and quality for multiple subsequent cereal crops (Armstrong et al. 1999b; Fillery 2001; Peoples and Craswell 1992). This yield benefit is mainly driven by high levels of residual fixed N; although legumes can also increase soil nitrate by removing less N than a non-legume crop, and improving soil organic matter and N losses compared to a fertiliser based system (Crews and Peoples 2005; Drinkwater et al. 1998; Tonitto et al. 2006). In addition, integrating forage legumes into cropping systems can also improve water infiltration, reduce erosion and evaporation (Giller et al. 2009), improve soil microbial activity (Peoples and Craswell 1992) and increase water use efficiency in regions with low and unreliable rainfall (Armstrong et al. 1999b). There are a range of factors that will potentially increase the importance of legumes in crop rotations including declining soil fertility, increased N costs, variable grain production due to climatic variability, emerging herbicide resistance and soil borne pathogens (Bell et al. 2012; Whitbread et al. 2009; White et al. 2013). Thus, forage legumes offer significant production benefits, with changes in commodity prices, resource availability and agro-climatic conditions likely to affect their future use in crop-livestock systems.

While this indicates that herbaceous forage legumes can contribute to intensification of smallholder crop-livestock systems, current adoption levels in Africa and Asia are low and potential soil N and fodder benefits remain unrealized (Horne and Stür 1997; Shelton et al. 2005; Sumberg 2002). This is especially evident when compared to temperate legumes, with only 5 M ha of subtropical and tropical legumes sown globally (Howieson et al. 2008) compared to 32 M ha sown to lucerne (*Medicago sativa*) globally (Bouton 2012) and further areas of other temperate legumes. Where adoption has been successful, such as in *Stylosanthes guianensis* in Southern China, the benefits are commonly either restricted to a small number of farmers or the regional distribution is limited (Connell et al. 2010; Franzel et al. 2005; Shelton et al. 2005; Stür et al. 2002). There is increasing recognition that limited adoption of forage legumes – and other technologies more broadly – is determined by both agro-ecological and socioeconomic factors (Giller et al. 2006; Ojiem et al. 2006). For warm season forage legumes, key agronomic factors limiting adoption include poor and unreliable agronomic performance driven by highly variable biomass production and N fixation, low and variable yield responses for subsequent cereal crops (Bell et al. 2017; Peoples and Herridge 1990) and poor persistence under grazing (Shelton et al. 2005). Limiting socioeconomic factors include failure to consistently deliver meaningful economic returns (Sumberg 2002), high labour requirements and poor labour-use efficiency (Komarek et al. 2015; Snapp and Silim 2002), competition with crops that provide a direct economic yield for food or for sale (Giller et al. 2009) and poor extension approaches (Horne and Stür 1997), including little consideration for the gendered nature of agriculture (Kerr et al. 2007). Thus, when considering the design and development of forage legume technologies, the fundamental farming system properties must be used to define the context into which the legumes are integrated, rather than being considered as constraints to adoption (Sumberg 2002). This is particularly important given forage legumes are likely to occupy a niche within smallholder farming systems rather than being a broadly applicable solution to lifting production and resource use efficiency (Elbasha et al. 1999; Ojiem et al. 2006; Sumberg 2002).

Identifying the potential niche for forage legumes requires researchers to look at farming systems from a broad perspective (Norman and Collinson 1985) and to understand the perceptions and priorities of individual farmers (Chambers 2008). This includes understanding the interactions between various biophysical elements (agro-climatic conditions, livestock, crops and forages), resource endowments (land, labour, capital and cash flow), economic feasibility (profitability, cash flow and markets) and the sociocultural context (preferences, values and labour organisation) (Lisson et al. 2010; Ojiem et al. 2006) (Figure 1.1). While not considered in this thesis, landscape, regional and global factors, such as those described in section 1.1, also influence mixed crop-livestock systems in the developing world (Herrero et al. 2010). Rather, this thesis focuses on key farm level interactions that are likely to affect forage legume adoption. At a biophysical level this includes declining land availability and soil fertility (Herrero et al. 2010), while key socioeconomic factors considered were increasing demand for livestock (Delgado 2005), income and risk (Ojiem et al. 2006), labour and management preferences (Snapp and Silim 2002) and gender (Quisumbing et al. 2015). Key biophysical and socioeconomic factors relevant to this thesis are discussed in more detail below.

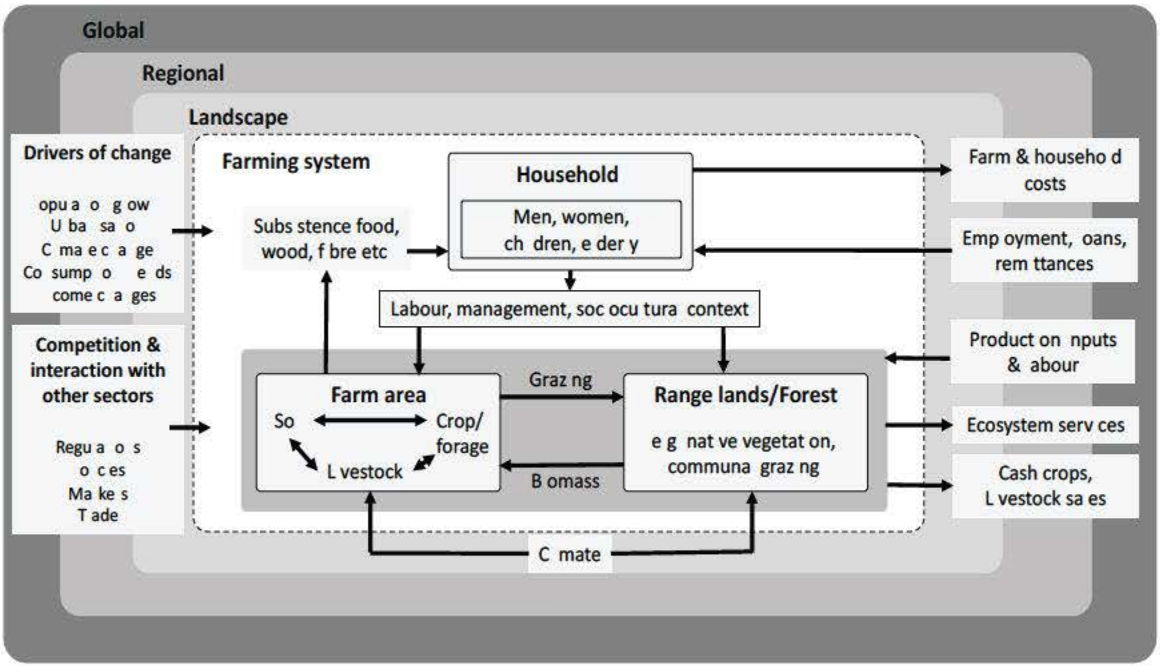


Figure 1.1. Schematic representation of the key resources and interactions in smallholder farming systems (modified from Herrero et al. 2010; Lisson et al. 2010; McCown and Parton 2006)

1.2. Agronomic performance of tropical and subtropical forage legumes

While temperate forage legumes can increase crop and livestock production in temperate farming systems, similar findings have not widely established for tropical legumes in either tropical or subtropical farming systems. The production benefits of forage legumes are predominantly driven by two key factors, biological N fixation and the production of high quality biomass for fodder, with both of these factors determining inputs of fixed N (Peoples et al. 2012). Research in Australia has demonstrated that, while warm season forage legumes can contribute significant amounts of fixed N (Peoples and Herridge 1990; Rochester et al. 2001), their performance has generally been disappointing with a low proportion of N derived from atmospheric N_2 (%Ndfa; <50%) and mean inputs of fixed N commonly <50 kg shoot-N/ha (Bell et al. 2017; Peoples et al. 2012; Peoples and Herridge 1990). This poor performance has been attributed to a range of factors including low rainfall and poor biomass production, poor nodulation and high N fertility soils which reduce N fixation levels (Armstrong et al. 1999a; Armstrong et al. 1997; Bell et al. 2017; Rochester et al. 1998; Rochester et al. 2001; Unkovich et al. 2010; Vallis and Gardener 1985). In commercial farming systems, such as those in northern Australia, these high levels of soil N are partly because the long fallows used to accumulate soil water also build up soil mineral-N which, if not rapidly depleted, reduces the reliance of legumes on N fixation for growth and thus results in lower net inputs of fixed N (Peoples et al. 2001). Yet, in areas with variable rainfall there is a tradeoff between depleting soil N prior to sowing and maintaining sufficient soil water to sustain legume growth (Armstrong et al. 1997; Bell et al. 2012; Whitbread et al. 2005). While these constraints are important in dryland production systems, in irrigated systems, rapid legume growth and depletion of soil N can result in N inputs of 180-240 kg shoot-N/ha (Rochester et al. 2001). Thus, subtropical and tropical forage legumes can contribute large amounts of fixed N, however under dryland conditions management and seasonal conditions determine the potential N inputs and production benefits.

While warm season forage legumes can contribute useful amounts of fixed N, the next step is converting this N benefit to meaningful increases in crop and/or livestock production. When legumes are green or brown manured they can increase the yield and grain quality of multiple subsequent crops (Armstrong et al. 1997; Peoples et al. 1995), with yield increases of 0.3-4.1 t/ha recorded for cereal crops immediately after a legume rotation (Armstrong et al. 1999b; Dalgliesh et al. 2010; Peoples and Herridge 1990). However, maximising these production benefits requires the subsequent crop to have sufficient yield potential to capture the benefits of the additional N (Bell et al. 2017) and for N supply and crop N demand to be synchronised (Crews and Peoples 2005). Rotation and soil water management is also critical as forage legumes can increase the likelihood of moisture stress for the subsequent crop (Armstrong et al. 1999b; Whitbread et al. 2005). Despite the potential increases in crop production, smallholder farmers often favour allocating legume shoot biomass to increasing livestock production (Giller et al. 2009). However, this significantly reduces the N benefit to crop production, as cutting and removing shoot biomass for fodder removes 60% of above ground legume N (Peoples et al. 2012). Consequently, when legume shoot biomass is removed, net inputs of fixed N and increases in crop yield haven’t been consistently achieved, with subsequent grain yield ranging from -30 to +20% compared to a non-legume rotation (Jones et al. 1996; Nyambati 2002; Oikeh et al.

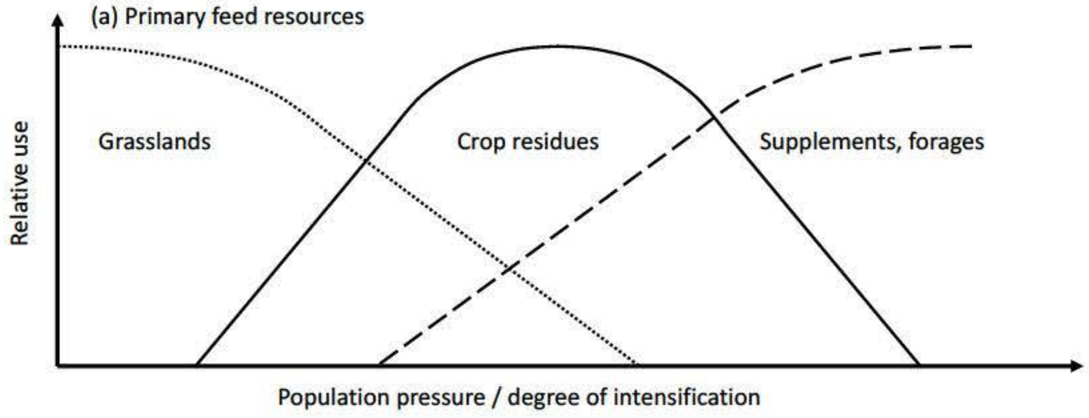
1998; Smyth et al. 1991). Thus, while forage legumes can increase crop yields and livestock production, there are large trade-offs associated with allocating legume biomass to either soil N or livestock fodder (Rodriguez et al. 2017).

1.3. Sociocultural and economic factors affect forage legume impacts

The agronomic performance of forage legumes is relatively well researched (Giller 2001; Peoples et al. 2012; Peoples and Herridge 1990; Sumberg 2002; Whitbread and Pengelly 2004) compared to the sociocultural and economic factors that also define the potential adoption and impacts of forage legumes (Connell et al. 2010; Horne et al. 2000; Maxwell et al. 2012; Ojiem et al. 2006; White et al. 2013). This thesis will also focus on key changes which are likely to affect future forage legume use in mixed crop-beef production systems, including declining land and labour availability and increasing demand for livestock products, as well as the need to develop gender-sensitive pathways for sustainable livestock development (Herrero et al. 2015).

For land availability, beef production often occurs on land with lower opportunity costs, indicating that the economic cost of the land is not as high as the physical land area indicates (Herrero et al. 2015). However, increasing population pressure in both Africa and Asia is reducing farm sizes and areas of communal land, as well as increasing land fragmentation (Ngongo 2011; Tittonell et al. 2009). Such pressures are likely to shift production from extensive systems to increasing levels of crop-livestock integration (Thornton and Herrero 2015). Forage legumes can contribute to this intensification, increasing the synergies between crop and livestock enterprises by increasing stover production for livestock, fodder for draft animals, manure for crop production and reduce income risk (Dalgliesh et al. 2010; Giller et al. 2009; Herrero et al. 2010; White et al. 2013). Given this range of benefits and the key global changes which are driving the intensification of crop-livestock systems (Section 1.1), forage legumes could be an increasingly important source of fodder and soil N (Figure 1.2, Fernandez-Rivera and Schlecht 2002).

However, different farming systems respond to land constraints differently, depending on the range of choices available and the prevailing socioeconomic conditions. Herrero et al. (2014) demonstrated that, in the east African Highlands, very strong land pressure meant not much land was available for pastures or forages and, instead, land was preferentially allocated to food or cash crops. This shift to export-orientated farming of cash crops was most evident near urban areas (Herrero et al. 2014), indicating that the interaction between land availability and commodity prices influence the specialization, diversification or extensification of farming systems (Thornton and Herrero 2015). These variables, combined with the cost of labour relative to land returns define the range of choices available to farmers and whether farmers can develop cash generating activities with high land use efficiencies (Baltenweck et al. 2003; Herrero et al. 2014; McIntyre et al. 1992). Thus, while forage legumes are one intensification option, relative land, labour and capital costs will determine the development trajectories of different crop-livestock systems (Thornton and Herrero 2015).



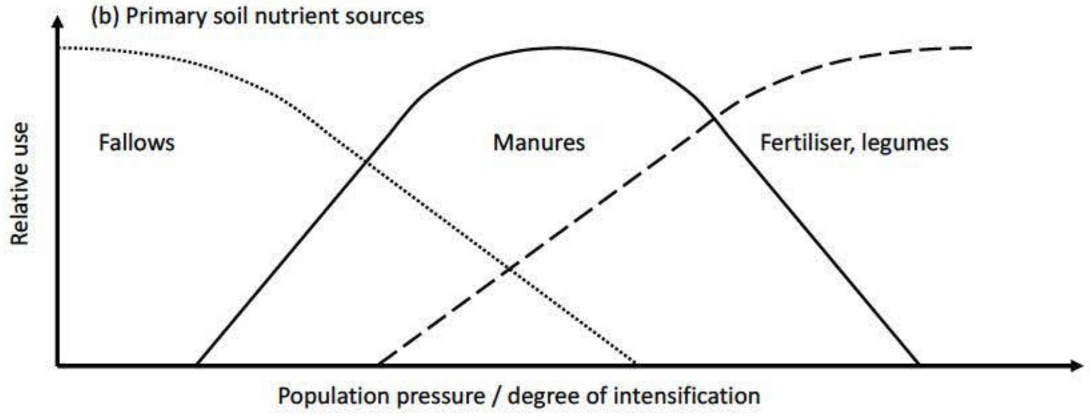


Figure 1.2. The relative importance of feed resources and soil nutrients in response to increasing population pressure or intensification of farming systems. Source: Fernandez-Rivera and Schlecht (2002)

Understanding the impact of forage legumes on labour inputs is critical, as labour is often the most limiting resource for a household (Barrett et al. 2002). This is particularly important given farms often have insufficient labour to invest in other soil fertility technologies such as making compost (Snapp and Silim 2002) or transferring manure to crop land (Bayu et al. 2005), and can spend up to 6 hours/day collecting fodder (Connell et al. 2010; Maxwell et al. 2012). For legume technologies, research indicates that, after productive and economic returns, labour is the most important selection criteria (Snapp and Silim 2002). However, the impact of forage legumes on net labour inputs and labour-use efficiency remains unclear, as estimated reductions for cut and carry labour of 1-1.5 hours/day (Ahmed 2012; Connell et al. 2010; Maxwell et al. 2012) fail to account for labour inputs across the full lifecycle of forage legume production and the impact on labour-use efficiency. Notably, forage intensification can reduce labour-use efficiency as, in western China, Komarek et al. (2015) found the forage intensification resulted in diminishing returns to labour. However, none of these studies account for gendered labour constraints which, for legume technologies in east Africa, were more important for women than men (Snapp and Silim 2002).

Given the gendered nature of agriculture, applying a gendered perspective to forage legume adoption and the potential benefits and trade-offs is critical. Gender responsibilities and roles will affect the intensification of crop-livestock systems as socially defined tasks and responsibilities determine what is considered appropriate for men and women (Quisumbing et al. 2014). Consequently, men and women face different constraints, have inequitable access to resources and markets, engage in different learning processes and innovation networks and have different innovation processes (Cardey and Garforth 2013; Chowa et al. 2013; Doss 1999; Meinzen-Dick et al. 2014; Quisumbing and Pandolfelli 2010). Critically, the triple role of women in productive, reproductive and community work means that women face larger labour constraints. Women commonly also have limited access and control over resources – notably land, labour and information – which enable innovation activities (Moser 1994). Differences in household responsibilities also mean that men and women consider different factors when adopting and adapting a new technology (Chowa et al. 2013; Moser 1994). To illustrate, legume research in Sub-Saharan Africa indicates that, compared to men, women are more interested in the impact on labour and subsistence products – food, wood and soil fertility – when selecting a suitable legume technology (Kiptot 2015; Snapp and Silim 2002). Consequently, gender affects farmers' motivations for trialing a new technology and whether they have sufficient resources to adopt and adapt it to their farming system.

1.4. Integrating forage legumes into crop-livestock farming systems in West Timor, Indonesia

In West Timor, Indonesia, smallholder farmers face similar constraints to farmers across Asia and sub-Saharan Africa (Section 1.1), including land constraints and fragmentation, declining availability of agricultural labour, soil degradation, low N inputs and high levels of food insecurity (FAO et al. 2010; Hosang 2014; Ngongo 2011). Despite these constraints, there are also significant economic opportunities driven by demand for beef from Java – beef prices have increased at 11% per annum over the past 10 years (Waldron et al. 2015) – and Indonesian government policy identifying East Nusa Tenggara (ENT) province as a key beef producing region. Previous research in West Timor indicates that forage legumes produced under dryland conditions can contribute to addressing these opportunities and constraints, with a range of tropical species identified as being able to contribute to intensifying crop-livestock systems in West Timor (Dalgliesh et al. 2010; Nulik et al. 2013).

Previous forage legume research has focused on maize-cattle systems, which are the dominant mixed crop-livestock system in West Timor (Dalgliesh et al. 2008; Dalgliesh et al. 2010; Nulik et al. 2013). Farmers commonly grow one maize crop – their staple food – intercropped with grain legumes and vegetables during the wet season from

December to April (Ngongo 2011), when they receive 400-2,300 mm of rain (Nulik et al. 2013). After maize harvest, farmers then leave their farm land to weedy fallow during the extended dry season, providing low quality feed to livestock. Dalgliesh et al. (2008) demonstrated that forage legumes could be used to improve this post-maize fallow, as the high plant available water capacity (PAWC) of the soils (144-308 mm to 180 cm depth; Nulik et al. 2013) meant that substantial amounts of soil water (i.e. 145 mm) were still available for forage production after the maize had been harvested. This provided the opportunity to establish forage legumes in relay or rotation with maize crops, with the legume producing between 1.5–5 t/ha of biomass (Nulik et al. 2013). This biomass provided two key opportunities; increase liveweight gain of Bali cattle (*Bos javanicus*) or increase staple crop production. Where male Bali calves were fed forage legume supplements during the dry season they gained 220 g/day compared to tether-grazed animals which lost 64 g/day (Dalgliesh et al. 2010). When this biomass was allocated to increasing soil fertility, forage legume butterfly pea (*Clitoria ternatea*) increased maize grain yield by 0.2-2.7 t/ha (Dalgliesh et al. 2010; Nulik et al. 2013). Importantly, when biomass was cut and removed for fodder, there was no increase in maize yield (Dalgliesh et al. 2010). Thus, while forage legumes can contribute to increasing crop or livestock production in West Timor, there appear to be significant trade-offs associated with biomass management.

Although there are a range of tropical forage legumes which can increase crop and livestock production in West Timor, research is yet to consider the socioeconomic factors which will define their potential role in crop-livestock systems and what level of on-farm impacts are achievable. At the farm level, forecast changes in land and labour availability in West Timor (Djoeroemana et al. 2007; Ngongo 2011) will affect future adoption trajectories. In addition, production preferences, commodity and input prices will also affect the economic benefits and opportunity cost of forage legume production (Baltenweck et al. 2003; Giller et al. 2009). Comparing these benefits and constraints with other forages or soil amelioration options will help elucidate the potential niche for forage legumes in West Timor. For example, in Sub-Saharan Africa research indicates that tree, grain and herbaceous forage legumes each offer a different set of benefits and constraints to smallholder farmers. In West Timor, tree legume leucaena (*Leucaena leucocephala*) is an increasingly important source of fodder, however, its adoption is currently constrained by insufficient labour for cut and carry systems and the availability of large areas of communal grazing land (Kana Hau et al. 2014). Importantly, gender relations in the predominantly patrilineal systems of West Timor (Ngongo 2011) will determine the distribution of benefits and trade-offs of forage legume production. In West Timor, women are predominantly responsible for reproductive and community roles while also contributing significant amounts of labour to crop and small livestock production (Oedjoe 2006). Yet, a new technology, such as forage legumes, can alter the division of on-farm labour, shifting tasks from men to women or vice versa (Quisumbing et al. 2015). Thus, the interactions between production impacts, resource availability, preferences and gender need to be elucidated to understand the distribution of impact and trade-offs of forage legume production in West Timor.

1.5. Justification of the project

Despite the potential production and economic benefits of introducing forage legumes to crop-livestock systems, adoption of forage legumes remains low and claims by Sumberg (2002) that forage legumes have largely failed smallholder farmers remain true in some regions (Shelton et al. 2005; White et al. 2013). While there is increasing recognition that production, economic and sociocultural factors define potential adoption trajectories (Ojiem et al. 2006), for forage legumes there remains limited research into the interactions between these factors. Critically, there is also little understanding of how gender roles influence forage legume preferences (Snapp and Silim 2002) and how men's and women's preferences may influence the adoption, management and impacts of forage legumes. Yet, increasing pressures for smallholder farmers to produce more grain or animal products without using more resources (Section 1.1) demonstrate the importance of understanding the potential for forage legumes to contribute to intensification of crop-livestock systems.

In general, there is little research on the impacts of forage legumes on whole farm production and household income, risk and resource allocation and how these differ with legume management, farm type and gender (Ojiem et al. 2006; Quisumbing et al. 2014; Snapp and Silim 2002; Sumberg 2002; World Bank 2009). This thesis aims to understand the integration of herbaceous forage legumes into smallholder crop-livestock farming systems and the potential impacts on whole farm production and the livelihoods of male and female smallholder farmers. Thesis chapters are presented in a journal format, with a review of relevant literature at the start of each chapter, the implications and importance of this thesis are discussed in the General Discussion (Chapter 7).

This thesis will:

1. Quantify the maximum potential impact of legume biomass management (retained vs. removed) on legume dry matter production, N inputs and subsequent yield benefits when environmental conditions are non-limiting (Chapter 2 and 3). These chapters use a field experiment and incubation study in south east Queensland, Australia, to investigate how preferentially allocating legume N to increasing soil N or livestock production affect soil N and subsequent crop yield.

2. Simulate and quantify forage legume performance across a range of agro-climatic conditions in West Timor and the impact of biomass management (retained vs. removed) on subsequent maize yield (Chapter 4).

3. Simulate and quantify the production and economic impacts of forage legumes for six case study farms in West Timor (Chapter 5). Participatory evaluation of simulation outputs was also used to assess farmers' perceptions of forage legume scenarios.

4. Evaluate how gender and farm type affect the benefits and constraints of forage legume production (Chapter 6). This work will also demonstrate the effectiveness of using a gender lens in farming systems research.

A mixed methods approach was used to assess the broad impacts of forage legumes on smallholder farming systems (Figure 1.3). Such an approach was chosen as mixed methods enable 'comprehensive analysis that can balance persuasive, generalizable analysis with nuance and complexity' (Jacobs 2003, p. 14), which is critical given previous research has largely failed to assess the farming system and household impacts and trade-offs of forage legume production. Thus, both qualitative and quantitative data was analysed and interpreted, with the range of methods used broadening and strengthening the study (Yin 2003).

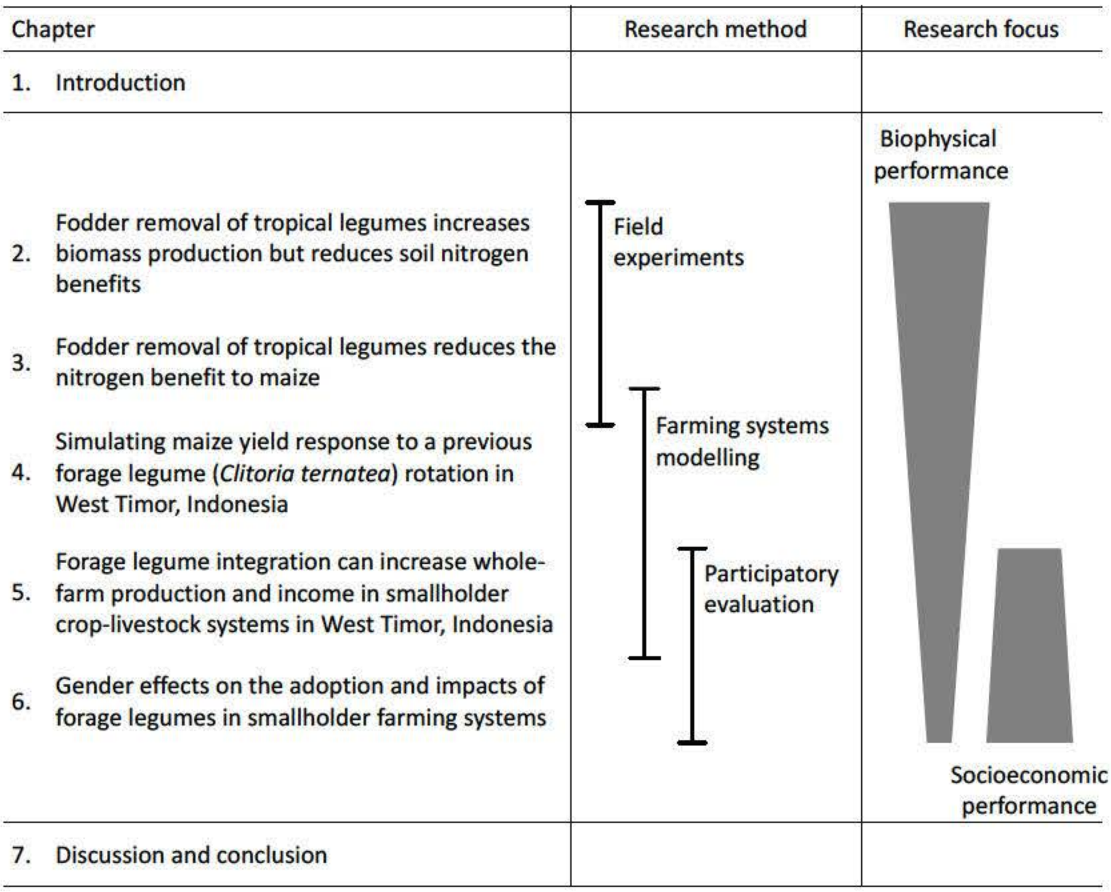


Figure 1.3. Schematic representation of the thesis layout, research methods and research focus demonstrating linkages between biophysical and socioeconomic research.

Field experiments and farming system simulations were used to assess the biophysical performance of forage legumes for a range of management options and agro-climatic conditions. Providing insight into the spatial and temporal performance of forage legumes (Holzworth et al. 2014). Building on this, the impacts and trade-offs of forage legumes on whole farm production and income were assessed using bio-economic and participatory modelling. The bio-economic modelling tested the long term performance (10 years) of forage legume management, identifying interactions between the biophysical and socioeconomic impacts of forage legumes (Lisson et al. 2010) while, the participatory modelling provided local social and biophysical context to the simulations (Sterk 2007). Finally, participatory on-farm evaluation provided insight into the gendered nature of forage legume adoption, allowing researchers to understand the perceptions and priorities of individual farmers depending on gender, farm type and agro-climatic conditions (Chambers 2008; Quisumbing and Pandolfelli 2009). While smallholder farming systems in West Timor, Indonesia, were the primary focus of the thesis (Chapters 4, 5 and 6), the field experiment (Chapters 2 and 3) was conducted in south east Queensland, Australia, as it allowed for more intensive data collection, more accurate analysis and minimized quarantine issues for soil and plant analysis. Importantly, differences in rainfall between West Timor (Chapter 4) and south east Queensland (Chapter 3) were mitigated by regularly irrigating the experiment, and the soil type (Black Vertosol, Isbell 1996) is also found in West Timor (Nulik et al. 2013). Together, this mixed methods approach should provide a more holistic assessment of the complexities of integrating forage legumes into smallholder farming systems.

2. Fodder removal of tropical legumes increases biomass production but reduces soil nitrogen benefits

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2.1. Abstract

Forage legumes and the associated nitrogen (N) fixation can provide high quality fodder and increase soil N and subsequent crop yield in mixed farming systems. However, large trade-offs exist between allocating legume N to crop or livestock enterprises. We investigated the impact of legume biomass management (retained vs. cut and removed) on potential soil N inputs under irrigated conditions for key warm season legumes, butterfly pea (*Clitoria ternatea*), burgundy bean (*Macroptilium bracteatum*), centro (*Centrosema pascuorum*), lablab (*Lablab purpureus*) and soybean (*Glycine max*) and a maize (*Zea mays*) control at Gatton, in south east Queensland. We found that the forage species produced 11-13 t DM/ha when shoot biomass was retained compared to 10-22 t DM/ha when shoot biomass was cut and removed multiple times. Forage species fixed 289-543 kg plant-N/ha when shoot biomass was either retained or removed. Cutting and removing forage legume shoot biomass removed 240-530 kg shoot-N/ha resulting in net N inputs of -116 to + 50 kg N/ha. Consequently, when shoot biomass was removed there was little or no increase in subsequent N mineralization and soil N compared to the cereal control. Despite this, centro was best suited to achieving a soil N benefit when biomass is removed. In comparison, when biomass was retained an additional 50-100 kg N/ha mineralised between the legume ley and subsequent summer cereal crop, with butterfly pea contributing the largest amount of fixed N. Thus, realizing these N benefits in dryland crop-livestock systems will require effective management of both forage legume and crop rotations.

Additional keywords: subtropical, legume ley, hay, cut and carry, fodder, green manure

2.2. Introduction

Forage legumes have been an important part of temperate crop-livestock systems for many years, with annual and perennial legumes widely grown in phased rotations with cereal crops (Angus and Peoples 2012; Kirkegaard et al. 2011; Puckridge and French 1983). Yet, similar systems have not been widely established in tropical and sub-tropical regions for either commercial or smallholder farming systems (Howieson et al. 2008; Sumberg 2002). Currently, the relatively small area of tropical forage legumes (~5 M ha) is predominantly used for high quality livestock feed (Franzel et al. 2005; Howieson et al. 2008; Shelton et al. 2005; Whitbread et al. 2009). However, reports suggest that adoption will increasingly depend on their ability to increase subsequent crop grain yield, especially in regions with declining soil fertility and increasing input costs (Armstrong et al. 1999b; Bell et al. 2012; Whitbread et al. 2009; White et al. 2013). Given the high and sustained returns from livestock and evidence of declining soil fertility (Lal 2004; Whitbread et al. 2009), the trade-offs between allocating legume nitrogen (N) to crop or livestock enterprises will determine how legume residues are managed.

In mixed farming systems, the trade-offs between allocating legume N to crop or livestock enterprises are primarily driven by net inputs of fixed N, which are a factor of dry matter production, the percentage of plant N derived from atmospheric N_2 (%Ndfa), and the proportion of legume N removed through livestock production (Peoples et al. 2012). Where legume N is allocated to crop production, tropical forage legumes can contribute up to 380 kg fixed-N/ha year^{-1} (Peoples et al. 1995), although inputs of <50 kg shoot fixed-N/ha year^{-1} are more common (Giller 2001; Peoples et al. 2012; Peoples and Herridge 1990). Removing legume biomass for hay conservation or cut and carry fodder considerably reduces the net inputs of fixed N, as 60% of aboveground biomass is commonly removed (Peoples et al. 2012). For example, in south-eastern Australia removing vetch (*Vicia villosa*) biomass for hay conservation removed 71-89 kg N/ha, leaving net inputs of fixed N of 6-41 kg N/ha (Peoples et al. 2012). Net N inputs are also achievable for warm season legumes, with mucuna and stylo hay increasing soil N at subsequent crop planting by 1-100 kg N/ha compared to a cereal or weedy fallow (Oikeh et al. 1998; Whitbread et al. 2004). However, other studies indicated that cutting and removing shoot biomass resulted in net N export and no increase in soil N (Nyambati 2002; Smyth et al. 1991). Thus, legume management has a large impact on N inputs, with reports indicating that net inputs of fixed N can't be consistently achieved when legume biomass is cut and removed for fodder.

Few publications have quantified the N inputs for tropical forage legumes when shoot biomass is cut and removed for fodder (Bell et al. 2017; Jones et al. 1996; Oikeh et al. 1998; Whitbread et al. 2004) and none compare the impact of biomass management (retained vs. removed) on potential N inputs for key species in a common environment. Bell et al. (2017) reported that, in southern Queensland, net inputs of fixed N for lablab and burgundy bean cut and removed for fodder varied between years and sites, ranging from -105 to +76 kg N/ha for 16 site years. However, these legumes were grown under dryland conditions and consequently biomass production and N inputs were limited by plant available water (Bell et al. 2017). Thus, the potential biomass production and N inputs under non-water limited conditions (such as those often encountered in monsoonal environments) have not been quantified for key species lablab, centro, butterfly pea and burgundy bean when shoot biomass is either retained or cut and removed for fodder. Consequently, the impact of allocating legume biomass to crop or livestock production on potential soil N inputs remains unresolved for these key species.

This chapter assesses five tropical legume species to determine how biomass management (retain vs. cut and removed) affects dry matter production, legume N uptake, %Ndfa and soil N. Thus, this research assessed the trade-offs between fodder production and increasing soil N and identified the most suitable species and management practices to increase soil N or livestock production and whether dual soil N-fodder benefits are achievable where water is not limiting.

2.3. Methods

2.3.1. Experimental design

The experiment involved a rotation of five legume species and a maize control in the first year (Phase 1 – 12 Sept 2013-8 Apr 2014), followed by a bioassay oat cover crop (Phase 2 – 28 May-14 Aug 2014) to ensure even starting soil water for the subsequent bioassay maize crop (Phase 3 – 10 Oct 2014-6 Feb 2015), which was planted to evaluate the impact of legume treatments on maize yield (reported in Chapter 3). Supplementary irrigation was used for the legumes and maize control to maximise potential legume growth and N fixation and N mineralisation thus minimising the impact of water limitations on legume biomass production and N fixation.

To ensure that sufficient infrastructure was available to irrigate and measure plant N, %Ndfa and soil N, the experiment was conducted at the CSIRO Research Station Lawes in south east Queensland, Australia, (27˚32'24"S, 152˚20'20"E) on a Black Vertosol (Isbell 1996). This enabled quantification of potential legume production and N inputs and the impact on subsequent crop production (Chapter 3) when environmental conditions were not limiting. These potential production benefits (Chapter 2 and 3) provided a baseline against which legume production under dryland conditions in West Timor, Indonesia (Chapter 4) could be evaluated.

The field experiment was an incomplete split-split plot design with four replicates (Figure 3.1, Chapter 3). For the first phase, the main plots (24 × 6 m) were the five legumes (butterfly pea, burgundy bean, centro, lablab and soybean) and a maize control. Subplot (12 × 6 m) treatments for each of the legumes were either cutting and removing legume biomass (cut) or leaving legume biomass uncut (uncut). The maize control was not divided into subplots, with grain and stover removed from the entire main plot. After the legumes and the maize control, a bioassay oat crop was then planted across the experiment to ensure consistent soil water across all treatments (Phase 2). In addition, in-situ micro-plots and an oven incubation measured N mineralization post legumes.

2.3.2. Seasonal conditions

Irrigation was applied to the legumes and maize control (Phase 1) in lots of 15-20 mm, up to twice per week. This amounted to 634 mm of rain and irrigation during Phase 1, however not all treatments grew for the entire period. Soybean and lablab did not regrow after their respective cut and removal (149 and 64 days before legume termination) and the maize control was harvested 64 days before legume termination (Figure 3.2, Chapter 3). For the oat cover crop (Phase 2), there was 102 mm of rainfall during the subsequent fallow and oat crop and no irrigation was provided.

2.3.3. Legume management

Legumes and maize were planted on 12 September 2013 at recommended seeding rates and row spacings using a no-till tyned cone seeder (see Table 3.1, Chapter 3 for more details). Legumes were inoculated with recommended rhizobium strains with peat slurry (Nodulaid®, BASF). A basal application of single superphosphate (8.8% P, 11% S and 19% Ca) was applied prior to sowing.

Legume shoot biomass in subplots with shoot biomass removed was cut at 70 mm above ground level and removed from the plot at each cutting. The first cut was taken when legumes were approaching peak shoot biomass (started flowering), subsequent cutting depended on legume regrowth. Butterfly pea and burgundy bean were cut and removed three times; 76, 144 and 208 days after sowing (DAS) and centro was cut and removed twice (119 and 208 DAS). Lablab was cut and removed twice (82 and 144 DAS), after which it failed to regrow and was left to fallow. Soybean was cut and removed once (88 DAS), it did not regrow and was left to fallow.

At each time of cutting and at 56 DAS, legume DM production was measured by collecting shoot biomass in three 0.25 m^2 quadrats (0.75 m^2) in each replicate legume plot. Residual legume biomass remaining after cutting was also measured at termination using three 0.25 m^2 quadrats (0.75 m^2). Maize grain and shoot biomass was harvested and removed from replicate plots at maturity (144 DAS). Shoot biomass and grain yield was measured above the first node from a subsample from two adjacent 3 m lengths of crop row (4 m^2) in the center of each plot. All biomass and grain samples were dried at 80°C until constant mass was reached. These samples were used to measure DM, stover and grain production and tissue N content. After the final biomass cut 208 DAS (8 April 2014), legume subplots were terminated, with all maize and legume subplots sprayed with Glyphosate (450 g a.i./L) at 2 L/ha and Dicamba (500 g a.i./L) at 400 ml/ha. Two weeks after spraying, subplots with shoot biomass retained were mulched with a tractor mounted flail mower set 100 mm above ground level.

2.3.4. Measurement of plant N accumulation

Shoot N concentration (mg N g^{-1}) was analysed for all biomass samples using a calibrated Bruker™ Near Infra-red Spectrometer. Maize grain N was assumed to be 1.5% N (Muchow 1998). Legume N uptake for legumes with shoot biomass retained was calculated using N concentration at maximum biomass (144 DAS), when total N was expected to be highest. Subplot shoot N when biomass was removed was calculated using shoot N at cutting.

Total uncut shoot N = [(shoot DM at termination) x (shoot %N/100)] [1]

Total cut shoot N = [(Cut 1 shoot DM) x (Cut 1 shoot %N/100)] + [(Cut 2 shoot DM) x (Cut shoot %N/100)] + [(Cut 3 shoot DM + Cut 3 residual DM) x (Cut 3 shoot %N/100) [2]

The total shoot N equation for biomass removed was altered accordingly when only one or two cuts were taken. To account for below ground plant N, total plant N for legumes with shoot biomass retained was calculated by multiplying shoot N by a root factor. As the impact of cutting on below ground N remains unclear (Unkovich et al. 2010), legume total plant N when shoot biomass was removed was calculated using estimates of below ground N from legumes with shoot biomass retained.

Total uncut plant N = [Total uncut shoot N] x [root factor] [3]

Total cut plant N = [Total uncut plant N–Total uncut shoot N] + [Total cut shoot N] [4]

The root factors for perennial legumes butterfly pea and burgundy bean (1.8) (45% below ground N; Peoples et al. (2012)) and annual legumes centro and lablab (1.49) (33% below ground N; Unkovich et al. (2010)) assumed partitioning of total plant N was similar to other annual and perennial pasture legumes. The root factor for soybean was 1.61 (38% below ground N) (Unkovich et al. 2010) and 1.58 for maize, based on mean below ground N of a range of temperate cereals (37% below ground N) (Wichern et al. 2008).

2.3.5. Nitrogen fixation by legumes

N fixation was estimated for the legumes using the ^{15}N natural abundance method (Unkovich et al. 2008). The proportion of plant N derived from atmospheric N_2 (%Ndfa) was calculated using equation [5], which compares the ^{15}N abundance ($\delta^{15}N$) of legume shoots ($\delta^{15}N$ legume) with the $\delta^{15}N$ of non N_2-fixing reference plants maize and sow thistle (*Sonchus arvensis*) ($\delta^{15}N$ of reference plant). The $\delta^{15}N$ of the reference plants were assumed to represent the ^{15}N abundance of the soil mineral N that the legumes used. Before maize harvest, reference plant $\delta^{15}N$ matched legume sampling dates, maize harvest reference plant $\delta^{15}N$ was used for all subsequent sampling dates.

$$\%\text{Ndfa}=100 \times (\delta^{15}\text{N of reference plant} - \delta^{15}\text{N legume})/(\delta^{15}\text{N of reference plant} - B) \quad [5]$$

The factor *B* corrected the fractionation of ^{14}N and ^{15}N between legume roots and shoots using legume shoot $\delta^{15}N$ when the plants depend solely on N fixation. The *B* values used were -1.65 ‰ (parts per thousand) for centro, -1.36 ‰ for lablab, -1.83 ‰ for soybean (Unkovich et al. 2008), -1.45 ‰ for butterfly pea (Ladha et al. 1996) and -1.40 ‰ for burgundy bean (Peoples, unpublished). The total amount of N fixed and the N balance after biomass was removed, was calculated as shown below:

Total N fixed = [Total plant N] x %Ndfa/100 [6]

N balance = [Total N fixed] – [Shoot N removed + stover N removed + grain N removed] [7]

The $\delta^{15}N$ values of the reference plants averaged 3.38 ± 0.52 (s.e.) for maize and 5.17 ± 0.16 for sow thistle. Sow thistle $\delta^{15}N$ remained relatively constant throughout the experiment while maize $\delta^{15}N$ declined from 4.43 ± 0.50 (76 DAS) to 2.34 ± 0.54 at anthesis (not significant P=0.08). These values are all greater than +2 ‰, which is commonly considered the lowest reference $\delta^{15}N$ required to reliably measure N fixation (Unkovich et al. 1994).

2.3.6. Measurement of available soil N and water

Soil nitrate (NO_3^-) and water were measured prior to planting the experiment and then in each replicate plot after the legumes (only butterfly pea, centro and maize subplots are reported, see below). Soil samples were collected to 1.2 m for NO_3^- and 1.5 m for water content using a hydraulically driven 38 mm tube to collect three samples in each replicate plot. Samples were separated into 0-15, 15-30, 30-45, 45-60, 60-90, 90-120 and 120-150 cm, and then subsampled for NO_3^- and gravimetric water content analysis. NO_3^- samples were dried at 40°C for ≥ 3 days and then analysed using a 1:5 soil:water extraction (Rayment and Lyons 2011). Total soil N was calculated using bulk densities described for a soil that had previously been characterized for the experimental site for the APSoil database, this was soil Lawes No037 (APSoil) (Dalgliesh et al. 2012). Soil

N results are only presented for 0-45 cm, as >92% of NO_3^- was above 45 cm. Gravimetric water content samples were weighed immediately after sampling, dried in the oven at 105°C for ≥ 3 days and then reweighed. Volumetric soil water content was calculated using bulk densities described above (Dalgliesh et al. 2012).

2.3.7. Measurement of post legume mineralization using in situ micro-plots

N mineralization after the legume ley was evaluated for butterfly pea and centro as these are species that are well adapted and successful pasture legumes in Australia and Southeast Asia (Cameron 2005; Dalgliesh et al. 2010; Whitbread et al. 2005). As an oat cover crop was sown after the legume rotation to ensure even starting soil water for the subsequent maize crop (Chapter 3), post legume mineralization was measured in in-situ micro-plots which excluded crop roots. A PVC tube (10 cm diameter by 60 cm long) was installed in each replicate butterfly pea and centro subplot with shoot biomass removed or retained and each maize main plot. Tubes – or 'micro-plots' – were installed on 1 June by driving them 50 cm into the ground using a tractor-mounted hydraulic ram. To avoid soil movement micro-plots were trimmed to leave 20 mm above ground. After 108 days soil samples were collected from each micro-plot to a depth of 45 cm. Samples divided into 0-15, 15-30 and 30-45 cm and analysed for soil nitrate and gravimetric water content as described above. N mineralisation was calculated by subtracting soil N after the legume rotation from soil N in the micro-plots 108 days after installation.

2.3.8. Measurement of mineralization rates using an oven incubation experiment

An oven incubation evaluated the impact of legume treatments on N mineralisation rates. After legume termination (14 May), seven intact soil cores (32 mm) were collected in each butterfly pea and centro subplot and each maize main plot to 60 cm deep. Each core was placed in a PVC tube (33 mm diameter x 60 cm long) and sealed with a PVC cap on the base and 4 layers of plastic wrap at the top. Cores were stored at 4°C for 49 days until oven space became available, after which they were transferred to an oven at 33°C. The soils were incubated at 33°C to maximise the mineralization rate (Cabrera and Kissel 1988). Cores were re-wet to original weight every two weeks with distilled water. The soil cores were destructively sampled at seven times over the incubation period, 0, 14, 47, 76, 119, 191 and 365 days, with gravimetric water content and soil nitrate and ammonium measured for one tube from each subplot. Samples were analysed for gravimetric water content as described above. Ammonium (NH_4^+) and NO_3^- were extracted in a 2M KCl extraction (Keeney and Nelson 1982) and analysed colourimetrically with a skalar segmented flow analyser.

2.3.9. Statistical analysis

Analysis of variance in Genstat 16.1 (VSV International Ltd. Hemel Hempstead, UK) was used to determine statistical differences in soil N and water content for micro-plot and incubation studies, legume biomass production, N concentration, N accumulation and N fixation. Mean separation was tested using least significant difference (l.s.d) at $P<0.05$. N mineralization rates were assessed using linear regression with groups and an analysis of variance in Genstat 16.1 with maize as the reference level and time from the start of the incubation as the explanatory variable. All data were normally distributed and not subject to transformation.

2.4. Results

2.4.1. Dry matter production

The impact of cutting on cumulative above ground DM production varied between species. Centro and burgundy bean total DM production doubled when biomass was cut and removed instead of retained, increasing from 11-12 t DM/ha to 20-22 t DM/ha ($P<0.001$, Table 2.1). In comparison, cutting butterfly pea increased DM production by only 3.5 t DM/ha, while lablab produced similar amounts of biomass for both treatments. Consequently, when cut and removed, centro and burgundy bean produced at least 4 t DM/ha more than butterfly pea and 9 t DM/ha more than lablab ($P<0.001$). Thus, total shoot DM removed was higher for centro (21 t DM/ha) and burgundy bean (20 t DM/ha) than butterfly pea (14 t DM/ha) and lablab (10 t DM/ha); significantly more shoot biomass was removed from forage legumes than soybean (5 t DM/ha) ($P<0.001$). When biomass was retained, all forage species accumulated similar amounts of DM. Residual biomass at termination averaged 1.5 t DM/ha for legumes with shoot biomass removed, 12 t DM/ha for legumes with shoot biomass retained and 0.6 t DM/ha for maize.

Table 2.1. Shoot dry matter (DM), shoot N and total plant N for maize and legumes with shoot biomass retained or cut and removed. Mean values are shown ± standard error. Different letters indicate statistically significant (*P*<0.05) differences between species and shoot biomass management.

	Total accumulated DM and N						Removed DM and N			
Crop	Shoot DM (kg/ha)		Shoot N (kg N/ha)		Plant N (kg N/ha)^{B}		Shoot DM (kg/ha)		Shoot N (kg N/ha)	
Maize^{A}	16.6 (5.6)	ac	157 (57)	f	247 (90)	f	16.0 (5.4)	bc	74 (32)	d
Uncut legumes										
Butterfly pea	12.3 (1.4)	cde	346 (55)	cd	623 (100)	bc	0		0	
Centro	12.4 (0.6)	cd	315 (15)	cde	469 (22)	cde	0		0	
Lablab	11.5 (0.9)	cde	264 (21)	de	393 (31)	ef	0		0	
Burgundy bean	10.9 (0.6)	cde	259 (26)	de	466 (47)	cde	0		0	
Soybean	13.0 (2.7)	cd	374 (49)	bc	601 (79)	bcd	0		0	
Cut legumes										
Butterfly pea	15.8 (1.5)	bc	537 (54)	a	814 (75)	a	14.1 (1.0)	bc	486 (40)	ab
Centro	22.4 (1.5)	a	569 (19)	a	723 (19)	ab	20.8 (1.1)	a	530 (26)	a
Lablab	9.8 (0.6)	de	275 (15)	cde	394 (16)	ef	7.9 (1.3)	cd	239 (23)	c
Burgundy bean	20.0 (0.8)	ab	472 (31)	ab	679 (45)	ab	18.4 (0.9)	ab	439 (28)	b
Soybean	6.1 (1.2)	e	223 (20)	ef	435 (30)	de	5.0 (0.5)	d	191 (18)	c

[A] Maize grain and stover combined

[B] Calculated using a root factor to include below ground N

The DM accumulation rate for the forage legumes with shoot biomass retained peaked at 137-199 kg/ha day^{-1}, when shoot DM was 5-9 t DM/ha (Figure 2.1). After which, net DM accumulation slowed to 0-70 kg/ha day^{-1} when 11-12 t DM/ha had been accumulated. Peak growth rates for annuals centro (142 kg/ha day^{-1}) and lablab (199 kg/ha day^{-1}) tended to be higher than for perennials butterfly pea (137 kg/ha day^{-1}) and burgundy bean (129 kg/ha day^{-1}) when shoot biomass was retained.

Cutting increased DM accumulation rates for centro, butterfly pea and burgundy bean. When centro was cut after accumulating 9 t DM/ha, DM accumulation post cutting was 180-224 kg DM/ha day^{-1} compared to 15-47 kg DM/ha day^{-1} when biomass was retained. For burgundy bean, early cutting when only 4 t DM/ha had been accumulated had little effect on DM accumulation rates. When burgundy bean was cut for the second time, when uncut burgundy bean had accumulated 11 t/ha, cutting increased net DM accumulation from 0 kg DM/ha day^{-1} to 207 kg DM/ha day^{-1}. A similar trend was evident for butterfly pea. In comparison, after cutting there was no increased DM accumulation rates for lablab, while soybean did not regrow.

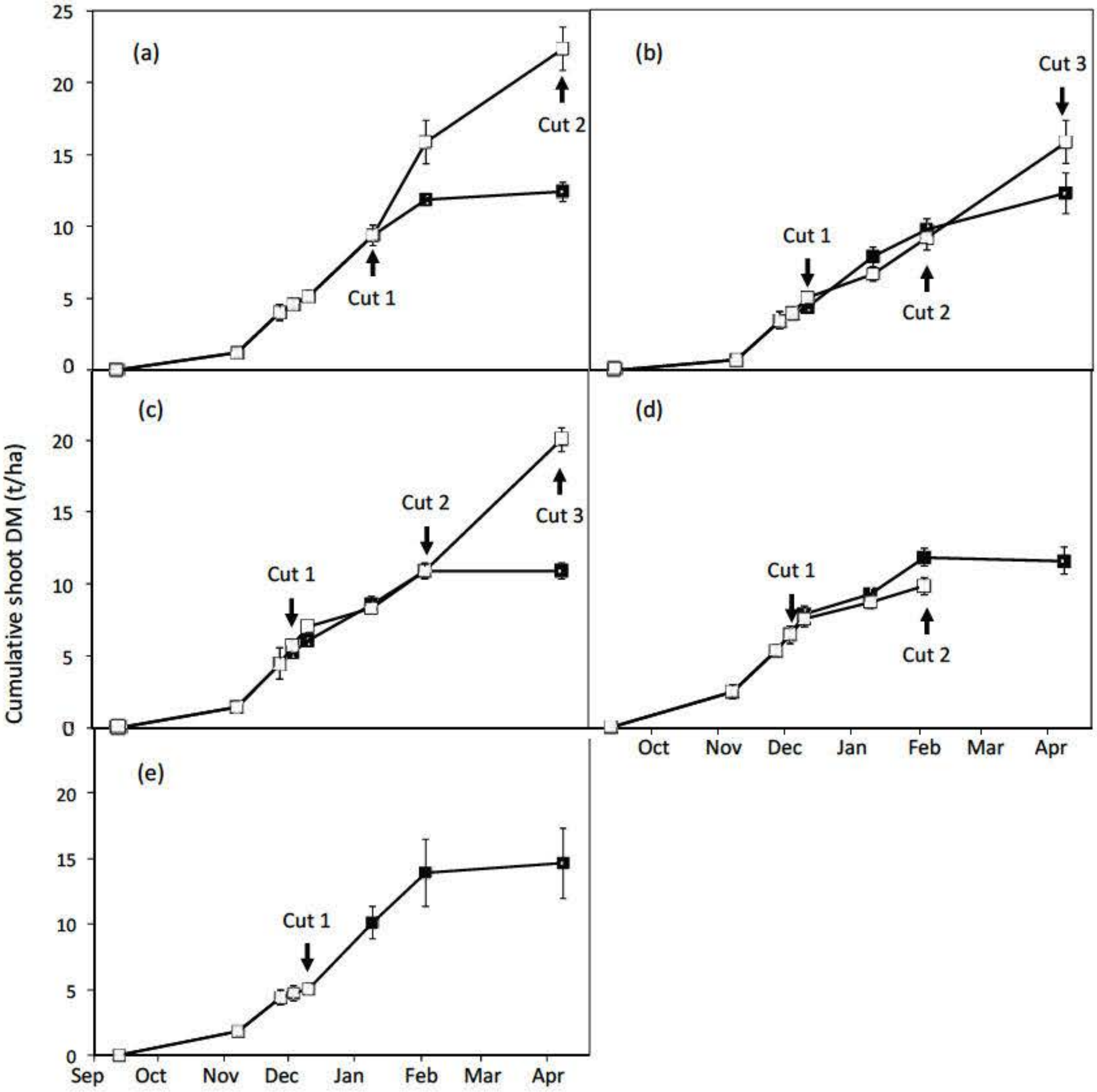

Figure 2.1. Cumulative shoot dry matter for (a) centro, (b) butterfly pea, (c) burgundy bean, (d) lablab and (e) soybean when legumes shoot biomass was retained (black squares) or cut and removed multiple times (white squares). Mean values are shown ± standard error.

2.4.2. N uptake

Total shoot N uptake and N accumulation rates reflected patterns in DM production. However, there were distinct differences in tissue N concentrations (Table 2.2). Butterfly pea, lablab, burgundy bean and soybean shoot N concentration decreased by 0.7-1% over the duration of the experiment, while centro shoot N concentration did not change (P<0.001). For the forage species, butterfly pea shoot N concentration was consistently 0.5% higher than other species when shoot biomass was cut and removed, while centro and butterfly pea had the highest shoot N concentrations when biomass was retained. At legume termination, the shoot N concentration for individual forage species was similar when shoot biomass was either retained or removed.

Table 2.2. Comparison of shoot N concentration (%) for legumes with shoot biomass removed or retained compared with maize. Mean values are shown ± standard error. Different letters indicate statistically significant (P<0.05) differences between species, biomass management and cutting timing.

	Shoot N%					
	Forage harvest 1		Forage harvest 2		Forage harvest 3	
Maize (biomass)	-		-		0.75 (0.26)	h
Uncut legumes						
Butterfly pea	-		-		2.88 (0.05)	cde
Centro	-		-		2.56 (0.06)	ef
Lablab	-		-		2.31 (0.04)	fg
Burgundy bean	-		-		2.37 (0.05)	fg
Soybean	-		-		3.02 (0.09)	bcd
Cut legumes						
Butterfly pea	3.98 (0.15)	a	3.19 (0.05)	bc	2.90 (0.03)	bcde
Centro	2.68 (0.04)	def	2.52 (0.06)	ef	-	
Lablab	3.32 (0.08)	b	2.31 (0.04)	fg	-	
Burgundy bean	3.09 (0.05)	bcd	2.37 (0.05)	fg	2.08 (0.09)	g
Soybean	3.79 (0.04)	a	-		-	

Cutting and removing shoot biomass increased total shoot N uptake by 50-80% for butterfly pea, centro and burgundy bean, equating to uptake of an additional 165-244 kg shoot-N/ha (*P*<0.001, Figure 2.2). In comparison, there was no significant difference in total shoot N uptake for lablab when shoot biomass was either retained or cut and removed. Cutting forage legumes removed 267-486 kg N/ha, leaving 8-51 kg

N/ha of residual shoot N at termination. In comparison, 259-346 kg N/ha of shoot residue remained following legumes with shoot biomass retained.

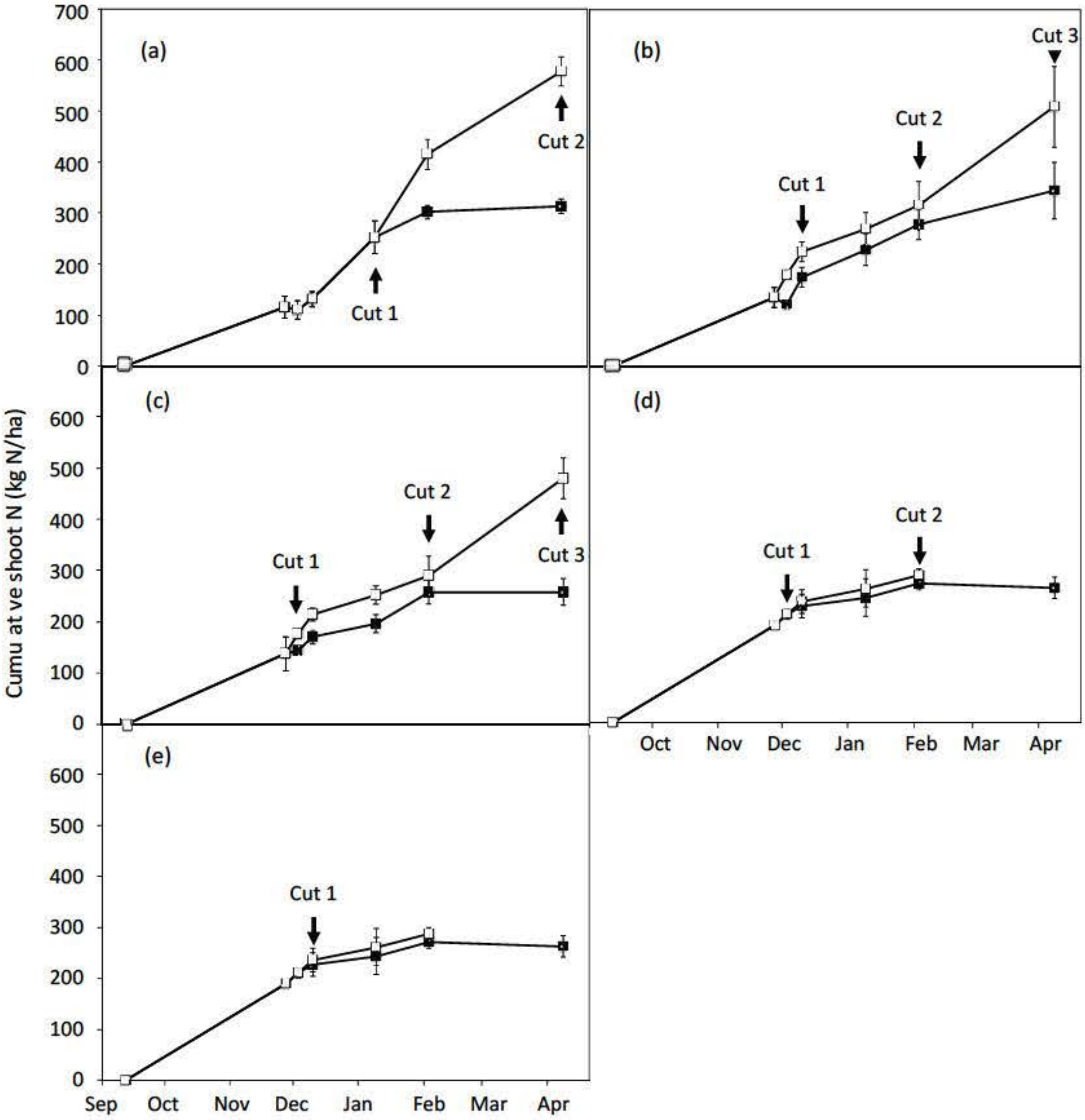

Figure 2.2. Cumulative shoot N for (a) centro, (b) butterfly pea, (c) burgundy bean, (d) lablab and (e) soybean when legumes shoot biomass is retained (black squares) or cut and removed multiple times (white squares). Mean values are shown ± standard error.

2.4.3. Nitrogen fixation

When shoot biomass was retained, %Ndfa was highest for butterfly pea, lablab and centro (70-89 %Ndfa, Table 2.3). In comparison, %Ndfa for burgundy bean with shoot biomass retained was 64%, which was 25 percentage points lower than butterfly pea

%Ndfa ($P<0.01$). Cutting and removing shoot biomass resulted in lower %Ndfa at termination, so that %Ndfa was 35-50 percentage points lower when biomass had been removed rather than retained ($P<0.01$). However, the impact of cutting and removing shoot biomass on %Ndfa varied between species. %Ndfa decreased for centro and burgundy bean after cutting but remained the same for butterfly pea. Notably, there was no significant correlation between biomass production and %Ndfa.

Table 2.3. The proportion of plant N derived from atmospheric N_2 (%Ndfa) for legumes with shoot biomass retained or cut and removed multiple times. Mean values are shown ± standard error. Different letters indicate statistically significant ($P<0.01$) differences between species, biomass management and cutting timing.

	Ndfa %		
	Forage harvest 1	Forage harvest 2	Forage harvest 3
Uncut legumes			
Butterfly pea	-	-	89 (9) ^{ab}
Centro	-	-	70 (10) ^{bc}
Lablab	-	-	82 (3) ^{ac}
Burgundy bean	-	-	64 (11) ^{c}
Soybean	-	-	62 (6) ^{cd}
Cut legumes			
Butterfly pea	63 (5) ^{cd}	59 (7) ^{cde}	54 (12) ^{d}
Centro	76 (4) ^{abcd}	34 (9) ^{ef}	-
Lablab	95 (2) ^{a}	n.d.	-
Burgundy bean	69 (11) ^{bcd}	24 (21) ^{f}	15 (22) ^{f}
Soybean	81 (6) ^{abc}	-	-

n.d., Not determined

Total shoot-N fixed by forage species was similar when shoot biomass was retained or removed (Table 2.4). However, for butterfly pea, centro and burgundy bean the amount of N fixed per tonne of shoot DM tended to be higher when shoot biomass was retained (15-25 fixed-N/t shoot DM) rather than removed (9-19 fixed-N/t shoot DM) (not significant). Total shoot-N fixed tended to be higher for butterfly pea, centro and lablab than for burgundy bean when biomass was either retained or removed, although only butterfly pea was significantly higher ($P<0.05$).

The N balance (defined as the N inputs from N fixation, minus the N removed in biomass or grain) for legumes with biomass retained (294 to 543 kg N/ha) was significantly higher than for legumes with biomass removed (-116 to 176 kg N/ha). When shoot biomass was retained, the highest fixed N inputs were butterfly pea (543 kg fixed-N/ha), which contributed 60% more fixed-N than other forage species. In comparison, the N balance when shoot biomass was removed was highly variable. While the N balance was positive for butterfly pea, lablab and soybean when shoot biomass was removed, it was negative for centro and burgundy bean.

Table 2.4. Total plant and shoot N fixed, N fixed per tonne of shoot dry matter and N balance for legumes with shoot biomass retained or cut and removed and maize with stover and grain removed. Mean values are shown ± standard error. Different letters indicate statistically significant (P<0.05) differences between species and shoot biomass management.

Legume	Plant N fixed[A] (kg N/ha)		Shoot N fixed (kg N/ha)		N fixed/t biomass (fixed-N/t shoot DM)		N balance (kg N/ha)	
Uncut legumes								
Butterfly pea	543 (95)	a	302 (53)	a	25 (2)	ab	543 (95)	a
Centro	336 (49)	c	225 (33)	abcd	18 (2)	bc	336 (49)	bc
Lablab	317 (17)	c	213 (12)	bcd	19 (1)	bc	317 (17)	bc
Burgundy bean	294 (45)	c	163 (25)	d	15 (2)	cd	294 (45)	bc
Soybean	382 (79)	bc	245 (49)	abcd	18 (3)	bc	382 (79)	b
Cut legumes								
Butterfly pea	495 (42)	ab	300 (7)	a	19 (1)	bc	46 (69)	ef
Centro	414 (41)	abc	296 (18)	ab	14 (1)	cd	-116 (45)	g
Lablab	289[B] (51)	c	242 (8)	abcd	27 (2)	a	50 (25)	ef
Burgundy bean	371 (46)	bc	178 (20)	cd	9 (1)	d	-51 (62)	fg
Soybean	364 (46)	bc	181 (12)	cd	30 (1)	a	176 (47)	cd
Maize	n.d.		n.d.		n.d.		-152 (55)	g

[A] Adjusted using root factors

[B] Calculated using %Ndfa from the first time of cutting only as %Ndfa from the second cut was unavailable

2.4.4. Soil N mineralization during incubation

During the incubation study, mineralization rates when shoot biomass was retained were 1.28 kg N/day for butterfly pea and 1.08 kg N/day for centro; both were significantly higher than the 0.77 kg N/day mineralised following maize ($P<0.05$ linear regression, Figure 2.3). In comparison, mineralisation rates when shoot biomass was removed were similar to the maize control. During the incubation NH_4^+ levels remained between 4-19% of total soil N for legumes with shoot biomass retained and 6-35% for maize and legumes with shoot biomass removed. Consequently, NH_4^+ remained low (<28 kg NH_4/ha) from 0 to 191 days of incubation, however after 365 days of incubation there was 80-110 kg NH_3/ha which accounted for 18-32% of total soil N.

Linear regression indicated that, for legumes with shoot biomass retained, it took 86 days to mineralize 100 kg N/ha, compared to 130 days following maize or legumes with shoot biomass removed. During the one-year incubation, total N mineralized in addition to mineralization in the maize control was 228 kg N/ha of butterfly pea and 154 kg N/ha for centro when shoot biomass was retained ($P<0.05$). This accounted for 37% of butterfly pea plant N and 32% of centro plant N. Notably, there were no significant differences between centro and butterfly pea in either the measured data or linear regression.

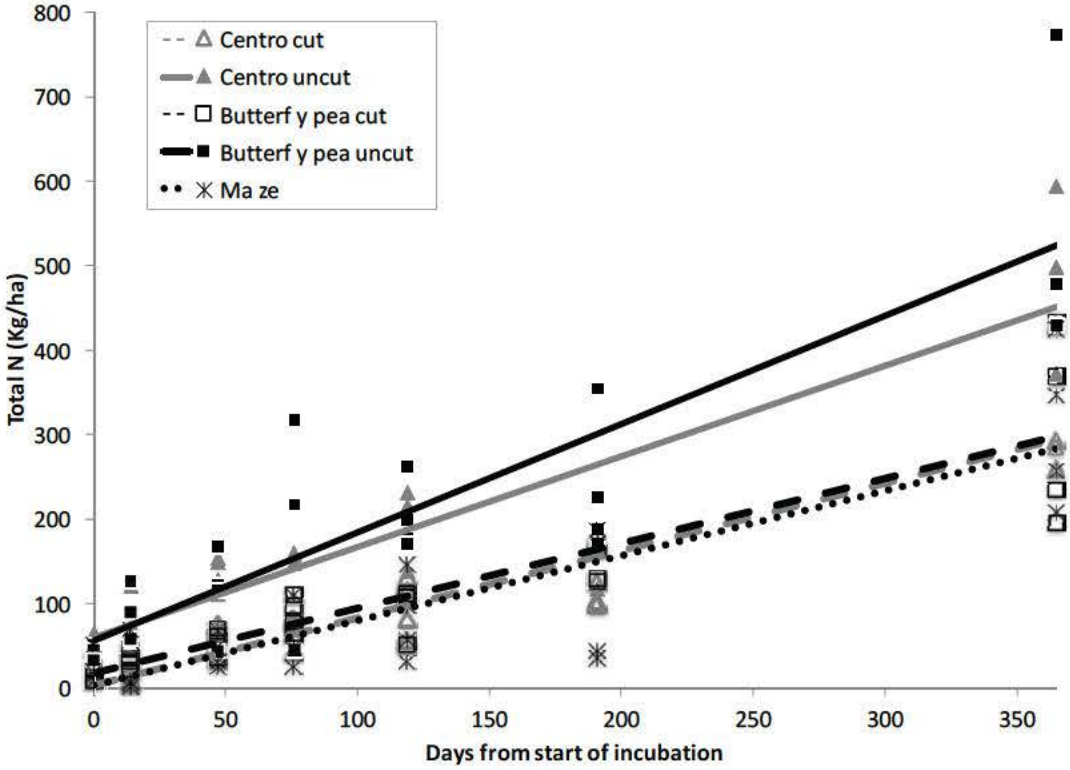

Figure 2.3. Total soil N (NH_4^+ and NH_3, 0-60 cm) during incubation of soil cores at 33°C following legumes with shoot biomass retained or cut and removed or a maize rotation; butterfly pea with shoot biomass retained, centro with shoot biomass retained, butterfly pea with shoot biomass removed, centro with shoot biomass removed, maize. Individual data points represent individual soil cores.

2.4.5. Soil N mineralization in-situ in micro-plots post legumes

For the post legume fallow, an extra 52-99 kg N/ha mineralized for legumes with shoot biomass retained compared to the maize control ($P<0.001$, Table 2.5). This equated to 18% of butterfly pea total plant N and 11% of centro total plant N mineralizing during the 108 days. In contrast, N mineralization for legumes with shoot biomass removed did not differ significantly from the maize control; although N mineralization for centro was similar when shoot biomass was retained or removed. Consequently, for butterfly pea with shoot biomass removed only 6% of retained plant N (the N contained in legume biomass below 70mm above ground level, which was retained after cutting) mineralized during this period, for centro 14% of retained plant N mineralized. Cutting and removing instead of retaining shoot biomass reduced N mineralization rates during the winter fallow for both butterfly pea and centro from 0.7-1.2 down to 0.4-0.5 kg N/ha day^{-1}; reducing total N mineralization by up to 84 kg N/ha. Note, the micro-plots averaged 22 mm more soil water than the field during the incubation (*P*<0.001), this may have caused the rate of mineralisation in micro-plots to be higher than mineralization in the field.

Table 2.5. Soil N (0-45 cm) after a rotation of maize and legumes with shoot biomass either retained or removed in micro-plots that measured in-situ N mineralization which was followed by a 108 day fallow. Mean ± standard error. Different letters indicate statistically significant (P<0.001) differences between species and shoot biomass management.

	Soil N (kg N/ha)		N mineralized in fallow (kg N/ha)	Legume plant N retained mineralised$^{n.s.}$ (%)
	Post legumes$^{n.s.}$	Post fallow		
Uncut legumes				
Butterfly pea	12 (4)	137 (14) ^{a}	125 (12) ^{a}	16 (4)
Centro	22 (9)	100 (15) ^{b}	78 (15) ^{b}	11 (4)
Cut legumes				
Butterfly pea	9 (2)	49 (7) ^{c}	41 (5) ^{c}	6 (4)
Centro	14 (3)	70 (10) ^{c}	56 (8) ^{bc}	14 (5)
Maize	21 (7)	47 (5) ^{c}	26 (5) ^{c}	n.d.

$^{n.s.}$ Not significant

2.5. Discussion

This paper reports that, under non-water limiting conditions, tropical forage legumes butterfly pea, centro, lablab and burgundy bean can fix 294-543 kg plant-N/ha year^{-1} when shoot biomass is either retained or cut and removed. However, hay conservation or cut and carry fodder significantly reduces these inputs of fixed N as we found that, after 239-530 kg shoot-N/ha was removed for fodder, the N balance ranged from -116 to +50 kg N/ha. Consequently, where shoot biomass was removed there was no significant increase in subsequent N mineralization compared to a cereal control. In comparison, where shoot biomass was retained, an additional 50-100 kg N/ha mineralized between the legume ley and the subsequent summer cereal crop.

2.5.1. Forage legume N fixation

In summer dominant rainfall regions, temperate and tropical legumes in irrigated cropping systems commonly fix 18-25 kg shoot N for every tonne of shoot DM produced (Peoples et al. 2001). We found that, when shoot biomass was retained, butterfly pea, centro and lablab N fixation efficiency was within this reported range. Thus, the performance of these irrigated legumes in a summer-dominant rainfall region (18-25 kg N shoot N fixed/t DM) was equivalent to the performance of temperate legumes under dryland conditions in winter-dominant rainfall areas (20-25 kg shoot N fixed/t DM) (Peoples et al. 2001, Rochester et al. 2001). In comparison, if tropical legumes are grown under dryland conditions, N fixation efficiencies are lower and more variable. For example, burgundy bean and lablab N fixation efficiency under dryland conditions at four southern Queensland sites ranged from 0-30 kg shoot N fixed/t legume DM, averaging 9 kg shoot N fixed/t DM (Bell et al. 2017; Bell et al. 2012), while in central Queensland lablab, burgundy bean and butterfly pea grown with limited supplementary irrigation fixed 7-8 kg shoot N/t DM (Armstrong et al. 1997). Thus, the potential N fixation efficiency for tropical forage legumes with shoot biomass retained (18-25 kg shoot N/t DM) is approximately double what is commonly achieved under dryland conditions (Armstrong et al. 1999a; Bell et al. 2017; Bell et al. 2012).

Compared to butterfly pea, centro and lablab, the N fixation efficiency for burgundy bean was poor, with only 15 kg shoot-N fixed/t DM. This low N fixation efficiency was driven by a relatively low %Ndfa (64%) compared to the other species. The reasons for this are unresolved, as other studies in southern and central Queensland found burgundy bean %Ndfa did not differ significantly from butterfly pea or lablab %Ndfa (Armstrong et al. 1997; Bell et al. 2017), although in these experiments %Ndfa was commonly <70%. Thus, under irrigation burgundy bean N fixation efficiency was similar to dryland systems, where 9-16 kg shoot N fixed/t DM is common (Peoples et al. 2001). In addition to a lower N fixation efficiency, it was also visually observed – although decomposition rates were not measured – that burgundy bean shoot biomass broke down slowly compared to the other legumes. Given burgundy bean shoot N% was 2.37%, which Peoples et al. (1990) indicates favours net mineralization, this slower decomposition may be due to high lignin and polyphenol contents (Fillery 2001; Tian and Kang 1998), although the reasons for the slow decomposition and low N inputs remain unclear.

Poor %Ndfa values (<50%) are commonly reported for tropical forage legumes, with the disappointing and variable performance often attributed to low rainfall and biomass production, high N fertility of soils and nodulation difficulties (Armstrong et al. 1999a; Armstrong et al. 1997; Bell et al. 2017; Rochester et al. 1998; Rochester et al. 2001;

Vallis and Gardener 1985). In southern Queensland, Bell et al. (2017) reported that, under dryland conditions, average %Ndfa for lablab (32%) and burgundy bean (21%) was low and highly variable, ranging from 0-68 %Ndfa for eight site years. Similarly, in central Queensland, Armstrong et al. (1997) reported %Ndfa for butterfly pea, lablab and burgundy bean was 30-45%. In comparison, under irrigated conditions we found that when shoot biomass was retained, %Ndfa was >80% for butterfly pea and lablab and 70% for centro, which is similar to 80% Ndfa reported for irrigated lablab in northern NSW (Rochester et al. 2001). This indicates that under irrigated conditions, which facilitate high biomass production and rapid depletion of soil N, tropical forage legumes can derive a large proportion of plant N from atmospheric N.

However, defoliating legumes can reduce N fixation, with the defoliation frequency and intensity determining the decrease in N fixation and the number of days for recovery of N fixation levels (Hartwig and Nösberger 1994; Menneer et al. 2004; Whiteman 1970). In this study, the impact of cutting and removing biomass on N fixation varied between species. Butterfly pea maintained %Ndfa at ~60% over three sequential cuts however, at termination %Ndfa following biomass removal (54%) was significantly lower than when biomass was retained (89%). In comparison, after one cut burgundy bean and centro %Ndfa more than halved and by termination cutting had reduced %Ndfa by 36-40 percentage points. Consequently, N fixation efficiency for butterfly pea, centro and burgundy bean tended to decrease by ~30% when shoot biomass was cut and removed, although this was not statistically significant. Therefore, removing shoot biomass can reduce %Ndfa however, the effect differs between species.

2.5.2. Forage legume total N fixed & removed

Despite the impact of cutting shoot biomass on %Ndfa, differences in biomass production of up to 10 t DM/ha meant that total shoot N fixed was similar when shoot biomass was either retained (160-300 kg N/ha) or removed (180-300 kg N/ha). While this level of fixation is at the upper end of values reported for these species (Peoples et al. 2012; Peoples et al. 1995), it is more than double what is commonly reported for dryland conditions in Queensland (0-60 kg shoot-N fixed/ha) (Armstrong et al. 1999a; Armstrong et al. 1997; Bell et al. 2017). Thus, under dryland conditions, the total amount of N fixed by butterfly pea, centro and lablab is less than half the amount that can potentially be fixed.

When below-ground N was accounted for, net inputs of fixed N when shoot biomass was retained were 543 kg fixed-N/ha for butterfly pea and 294-336 kg fixed-N/ha for centro, lablab and burgundy bean. Of this legume N, 23-32% was taken up by the subsequent maize crop (Chapter 3) and it is likely that a further 5-10% of legume N would become available for successive crops (Fillery 2001). However, reports suggest that 25-40% of legume N can be lost from green manures in tropical cropping systems (Crews and Peoples 2005; Glasener and Palm 1995; Peoples et al. 1995). Thus, to maximise the benefit of these large N inputs synchrony between N supply and crop demand and minimizing the risk of N losses are key. Crews and Peoples (2005) suggest that this can be achieved by (1) increasing crop N demand through good agronomic management, (2) manipulating N supply by adjusting the timing of green manure incorporation, manipulating residue quality and strategic fertiliser-N application, and (3) capturing excess inorganic N with catch crops. Thus, while large inputs >300 kg fixed-N/ha are achievable, maximizing the N benefit to subsequent crops requires effective management of legume leys, fallows and cereal crops.

Cutting and removing fodder reduced the N balance (N inputs from N fixation, minus the N removed in biomass) from >300 kg to ≤50 kg N/ha. This indicates that the amount of N removed for fodder (239-530 kg N/ha) was similar to the amount of plant N fixed (289-495 kg N/ha) when biomass was removed, and thus net N inputs weren't consistently achieved for these forage species when shoot biomass was cut and removed. Similar results have been found in dryland systems, with Bell et al. (2017) reporting a positive N balance in only three out of 19 site years, with an average N balance of -43 kg N/ha. Peoples et al. (2012) suggest that %Ndfa >65% is required to achieve net return of fixed N to the system as hay conservation commonly removes 60% of above ground biomass. Similarly, Bell et al. (2017) reported that a positive N balance for lablab and burgundy bean was only achieved with >58% Ndfa. For this experiment, subsequent maize N uptake (Chapter 3) indicates that for butterfly pea and centro an average %Ndfa of 55-60% achieved a positive N balance. Thus, a similar bench mark of 60-65% Ndfa appears to apply to both temperate and tropical pasture species under both dryland and irrigated conditions. However, given poor %Ndfa values (50%) are common, the likelihood of consistently achieving a positive N balance in hay conservation or cut and carry systems is low (Peoples et al. 2012).

Notably, the calculated N balance (Table 2.4) appears to underestimate net N inputs when shoot biomass is removed by >20 kg N/ha for butterfly pea and >200 kg N/ha for centro (Chapter 3). Whether this is because N inputs from below ground N or senescent material were underestimated remains unclear. Thus it remains unresolved as to whether N allocated to nodulated roots and rhizodeposits for these tropical species falls within the reported range of 33-45% when shoot biomass is retained or removed (Peoples et al. 2012; Unkovich et al. 2010). Given below-ground legume N can be an important source of N for subsequent crops (McNeill et al. 1998), further research is required to estimate below ground N for tropical forage legumes and how the shoot:root N ratio changes with cutting (Unkovich et al. 2010).

2.5.3. Effect of legumes on soil N

The impact of legume management on soil N varied for winter and summer crops. During the winter fallow an additional 50-100 kg N/ha mineralized in the micro-plots when centro and butterfly pea shoot biomass was retained, while no additional N mineralized when shoot biomass was removed. In contrast, during the subsequent summer maize crop an additional 130-170 kg N/ha mineralized when centro and butterfly pea shoot biomass was retained compared to an additional 47-70 kg N/ha when shoot biomass was removed (Chapter 3). In addition, the N benefit when shoot biomass was retained was large for the summer crop as the mineralization rate during the summer (1.9-2.3 kg N/ha day^{-1}) was higher than for the winter fallow (0.7-1.2 kg N/ha day^{-1}). This meant that 11-16% of centro and butterfly pea N had mineralized during the winter fallow, while the maize crop recovered up to 32% of legume N (Chapter 3). While higher soil temperatures increase N mineralisation, frequent irrigation during the maize crop may have also increased mineralisation (Cassman and Munns 1980; Peoples et al. 1995). Accordingly, the N benefit when shoot biomass was retained was available for the winter and summer crops but any N benefit when shoot biomass was removed was only realized during the summer crop (maize) (Chapter 3). Therefore, farmers have to manage interactions between shoot management, fallow length and soil conditions to maximise the N benefit to cereal crops.

In addition to in-situ mineralization, the incubation study demonstrated green manured legumes can increase soil N by >228 kg N/ha. However, N inputs are likely to be higher as, after 1 year, mineralisation in the incubation hadn't plateaued and only 35% of estimated legume plant N had mineralised. Net inputs of soil N were also underestimated when shoot biomass was removed as soil N did not differ from the maize control. Notably, the incubation failed to maximise mineralization as N mineralization rates in the incubation were lower than mineralization rates in the field during the maize crop (Chapter 3). This may be due to differences in soil water, soil disturbance and mulching of shoot biomass (Peoples et al. 1995).

The differences in the magnitude and timing of N release when shoot biomass was retained or removed in the in-situ microplots and incubation reflect the quantity and quality of plant residues. Green manured legumes decompose rapidly, with up to 40% of green residues mineralizing in 12 months (Fillery 2001). This is driven, in part, by the N content of the legume residues with values above 1.8-2% N favouring mineralisation and below 1.5% N favouring immobilization (Peoples and Herridge 1990). In this experiment, leaf N% (2.5-4.6%) favoured mineralisation while forage legume stem N % (1.2-1.6 %) favoured immobilization. Although root N % was not measured, cutting may reduce root N%, as Nyambati et al. (2009) reported that cutting lablab reduced root N from 2.2 to 1.3 %, shifting it from favouring mineralisation to immobilization. Critically, C:N ratio and the lignin and polyphenol content of plant residues also affect N mineralization (Fillery 2001; Tian and Kang 1998), although there is little evidence from other research that high lignin or polyphenol contents affect mineralization for the species in this study. Thus, understanding of how management affects below ground legume N and the magnitude and timing of N release requires further investigation and measurement of a wider range of factors which influence mineralisation and immobilisation.

2.5.4. Legume dry matter production

In addition to improving soil fertility, forage legumes can also increase livestock production (Shelton et al. 2005). In this study, cutting and removing fodder produced more biomass (average 17 t/ha) than retaining biomass (average 12 t DM/ha). Cut centro, burgundy bean and butterfly pea produced >15 t DM/ha in seven months, indicating that irrigated legumes can produce considerable amounts of high quality feed. In comparison, under dry land conditions in sub-tropical Australia these species commonly produce 2-5 t DM/ha, with a reported range of 1-9 t DM/ha year^{-1} (Armstrong et al. 1999a; Bell et al. 2012; Dalgliesh et al. 2010). Where farmers only plan to cut biomass once all species produced similar amounts of biomass. However, if multiple biomass cuts are required to feed livestock then centro, burgundy bean and butterfly pea perform best. This is particularly important in smallholder systems where fodder is commonly fed fresh rather than being stored as hay, which increases the importance of the timing of fodder availability (Budisantoso et al. 2004).

2.6. Conclusion

This study found that, under irrigated conditions, tropical forage legumes can contribute significant amounts of fixed N, resulting in net N inputs of 294-543 kg fixed-N/ha when legume shoot biomass is retained. In comparison, if biomass is removed for fodder, the amount of N removed can exceed the amount of N fixed, resulting in net N export. Comparing production objectives, if soil N is a priority then butterfly pea contributed the largest amount of fixed N. However, if fodder production is most important then butterfly pea, centro and burgundy bean are all suitable species. If dual soil N-fodder benefits are sought then centro is the most suitable species although, even then, there was a significant trade-off between fodder production and increasing soil N. However, under dryland conditions, reported N fixation efficiency and biomass production are half of what was achieved under irrigated conditions indicating that, under dryland conditions, the N benefit of tropical forage legumes are significantly below what can potentially be achieved. In conclusion, tropical forage legumes can fix substantial amounts of N and increase plant available N for subsequent cereal crops, however achieving these benefits requires effective management of legume-cereal crop rotations and livestock feeding practices.

2.7. Acknowledgements

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Higher Degree Research Thesis by Publication

University of New England

STATEMENT OF ORIGINALITY

We, the Research PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Higher Degree Research Thesis by Publication

University of New England

STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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3. Tropical forage legumes provide large N benefits to maize except when fodder is removed

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3.1. Abstract

Integrating tropical forage legumes into cropping systems has the potential to improve subsequent crop N supply, but removal of legume biomass for forage is likely to diminish these benefits. This study aimed to determine 1) under irrigated conditions the potential N inputs that can be provided by different tropical forage legumes to a subsequent cereal crop and 2) the residual N benefits once fodder had been removed. Available soil mineral N following tropical forage legumes lablab (*Lablab purpureus)*, centro *(Centrosema pascuorum*), butterfly pea (*Clitoria ternatea*) and burgundy bean

(*Macroptilium bracteatum*) and grain legume soybean (*Glycine* max) were compared with maize (*Zea mays*) when legume biomass was retained or cut and removed. After these legumes, a subsequent bioassay of an oat (*Avena sativa*) cover crop and a maize grain crop were grown and N uptake, biomass production and grain yield were compared among tropical legumes and the maize control. To determine N fertiliser equivalence values for subsequent maize crop yields different rates of fertiliser (0, 50, 100 and 150 kg urea-N/ha) were applied. Butterfly pea, centro and lablab with biomass retained increased subsequent unfertilised maize grain yield by 6-8 t/ha and N uptake by 95-200 kg N/ha compared with following a previous cereal crop, contributing equivalent to 100-150 kg urea-N/ha. When legume biomass was cut and removed, grain yield for the following maize crop did not increase significantly. Thus, when butterfly pea, centro and lablab biomass was retained rather than removed, maize accumulated an additional 80-132 kg N/ha. After fodder removal, centro was the only legume that still provided N benefits to the subsequent maize crop (equivalent of 33 kg urea-N/ha). Burgundy bean did not increase subsequent crop production when biomass was retained or removed – the reasons for this are unclear. Overall this study found a range of tropical forage legumes can contribute large amounts of N to subsequent crops, potentially tripling maize grain yield. However, when these legumes were cut and removed, the benefits were greatly diminished and the legumes provided little residual N benefit to a subsequent crop. Given the N trade-offs between retaining and removing legume biomass are large, quantification of the N inputs under livestock grazing or when greater residual biomass is retained may provide an alternative to achieving dual soil N-fodder benefits.

Additional keywords: subtropical, legume ley, hay, cut and carry, fodder, green manure

3.2. Introduction

Forage legumes can be an important source of N for subsequent cereal crop production. In tropical and subtropical regions, declining soil fertility and rising input costs have increased interest in the role of summer-growing rotations of annual and short-term perennial forage legumes to increase soil N and subsequent cereal crop production (Strong et al. 2006; Whitbread et al. 2009). In these regions, tropical forage legumes can provide large amounts of N – equivalent to 30-90 kg fertiliser-N/ha – and increase subsequent crop grain yield by 26 to 113% (Armstrong et al. 1999b; Dalgliesh et al. 2010; Peoples and Herridge 1990). However, growth conditions greatly influence legume N fixation and inputs, as well as subsequent crop N demand and yield responses. Because of these factors, assessments of the potential N benefits that tropical forage legumes can provide are often confounded.

There are a range of tropical legumes that can be used as forages in rotation with cereal crops. However, their potential N inputs and the benefit to subsequent cereal crops have rarely been assessed and where this has been done legume performance has been confounded by differences in environmental conditions including initial soil N status and water availability (Jones et al. 1996; Bell et al. 2017). For example, total N fixation for key tropical forage legume species under dryland conditions ranges from 0-161 kg fixed-N/ha/year (Armstrong et al. 1999a; Armstrong et al. 1997; Bell et al. 2017; Rochester et al. 2001). In comparison, much higher N inputs have been reported in irrigated lablab (243 kg fixed-N/ha/year) (Armstrong et al. 1999a; Armstrong et al. 1997; Bell et al. 2017; Rochester et al. 2001). Similarly, water availability and hence growth potential and N demand in subsequent cereal crops greatly influences the size of the potential N benefit from legumes (Bell et al. 2017). These factors also influence

N fertiliser equivalence values which, to our knowledge, remain unquantified for key tropical forage legumes in rotation with cereal crops. It remains unresolved whether there are differences amongst tropical forage legumes in terms of their potential N inputs and whether some species have a larger N fertiliser equivalence value and N benefit for subsequent crops when environmental conditions are not limiting.

While forage legumes can provide an important source of N for cereal crops (Bell et al. 2017), in crop-livestock systems the utilisation of forage legumes for livestock feed influences the N benefits to crop production. Tropical forage legumes are often used for hay production in commercial farming systems, while smallholder farmers commonly use them as cut and carry fodder (Jones et al. 1996). Removing this legume shoot material for fodder substantially reduces N inputs, as 60% of legume N is commonly removed from the field (Peoples et al. 2012). Despite the importance of these systems, the residual N benefit after legume biomass is removed for hay or cut and carry fodder is poorly understood. Elucidating the soil N trade-offs of retaining or removing legume shoot biomass is critical to assessing the value of preferentially allocating legume N to increasing crop or livestock production (Strong et al. 2006; Whitbread et al. 2009).

The study aimed to determine 1) the potential N inputs that can be provided by different tropical forage legumes to a subsequent cereal crop and 2) their residual N benefits once fodder had been removed under conditions which maximised both legume production and subsequent crop yield potential. This revealed differences amongst tropical forage legumes in terms of their N inputs and impacts on subsequent maize crop productivity and that biomass removal greatly diminishes the N benefit to subsequent crops.

3.3. Methods

3.3.1. Experimental design

The experiment involved a rotation of five legume species and a maize control in the first year (Phase 1 – 12 Sept 2013-8 Apr 2014), followed by a bioassay oat cover crop (Phase 2 – 28 May-14 Aug 2014) to ensure even starting soil water for the subsequent bioassay maize crop (Phase 3 – 10 Oct 2014-6 Feb 2015), which was planted to evaluate the impact of legume treatments on crop production. The experiment was conducted on a Black Vertosol (Isbell 1996) at the CSIRO Research Station Lawes in south east Queensland, Australia (27°32’24”S, 152°20’20”E). The legumes and maize control and the bioassay maize crop were provided with supplementary irrigation to both maximise potential legume growth and the response in the subsequent bioassay maize crop, thus minimising the impact of water limitations on legume growth and N fixation and subsequent crop N demand.

The field experiment was an incomplete split-split plot design with four replicates (Figure 3.1). For the first phase, the main plots (24 × 6 m) were the five legumes (butterfly pea, burgundy bean, centro*,* lablab and soybean) and a maize control. Subplot (12 × 6 m) treatments for each of the legumes were either cutting and removing the forage biomass (cut) or leaving the forage biomass uncut (uncut). The maize control was not divided into subplots, with grain and stover removed from the entire main plot. After the legumes and the maize control, a bioassay oat crop was then planted across the experiment to re-establish consistent soil water across all treatments (Phase 2). Following the oat cover crop, a bioassay maize crop was planted to assess relative N supplied from the previous legume (Phase 3). Each legume subplot (cut or uncut) was then split into four N fertiliser rate sub-subplot treatments (3 × 6 m); fertiliser was applied at 0, 50, 100 and 150 kg urea-N/ha. At the same time, the maize control main plots were divided into eight subplots with eight N fertiliser rates applied, which included four additional higher rates to those applied to legume sub-subplots to ensure maximum fertiliser response was achieved (250, 375, 500, 750 kg urea-N/ha). These increments of urea-N enabled N fertiliser equivalence values to be calculate at lower levels of N inputs (≤150 kg urea-N/ha) while ensuring maximum N-unlimited yields were achieved, providing scope to measure higher N inputs (>150 kg urea-N/ha). As maximum maize yields were achieved with <250 kg urea-N/ha these higher N rates are not presented.

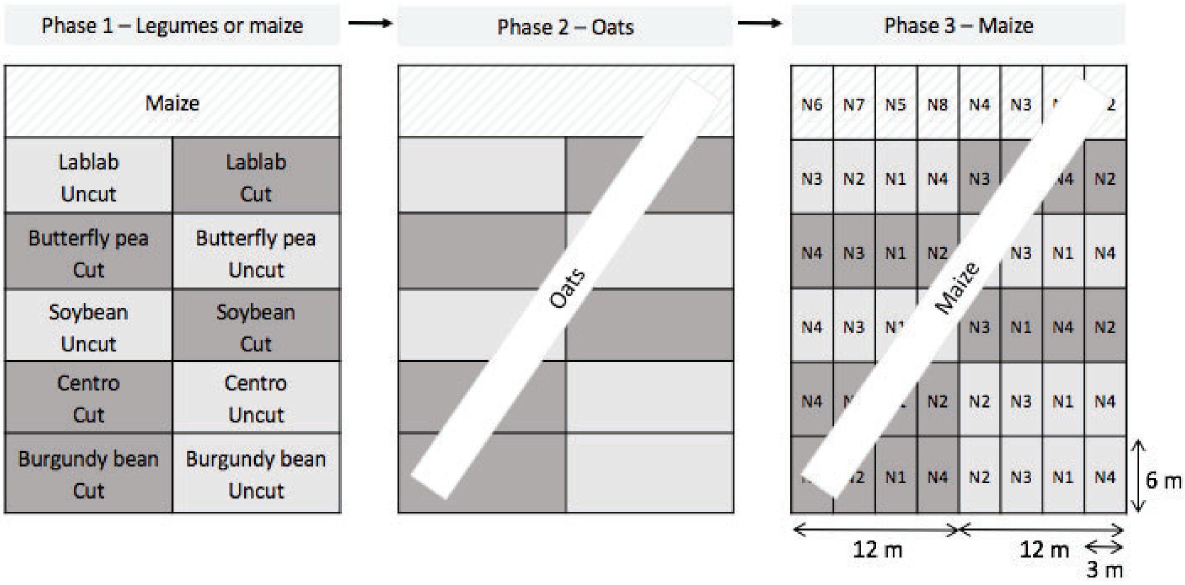

Figure 3.1. Experimental design showing the implementation of experimental phases and treatments; Phase 1 involving five legume species with biomass either retained (uncut) or removed (cut) and a maize control; Phase 2 where a oat cover crop was sown across all plots; and Phase 3 involving a maize bioassay crop which was also treated with a range of N fertiliser rates applied to legume sub-subplots and maize subplots (N1= 0, N2= 50, N3= 100. N4= 150 kg urea-N/ha), an additional four rates were also applied to maize subplots (N5= 250, N6= 375, N7= 500, N8= 750 kg urea-N/ha).

3.3.2. Seasonal conditions

Irrigation was applied as required based on estimates of crop requirements in lots of 15-20 mm, up to twice per week throughout the growing season for the legume phase and bioassay maize crop. During experimental phase 1 this amounted to 634 mm of rain and irrigation (Figure 3.2). However, not all treatments grew for the entire period, since soybean and lablab did not regrow after their respective cut and removal (149 and 64 days before legume termination) and the maize control was harvested 64 days before legume termination. During phase 2, there was 102 mm of rainfall during the subsequent fallow and oat cover crop and no irrigation was provided. During phase 3, 560 mm of rain and irrigation was provided to the bioassay maize crop.

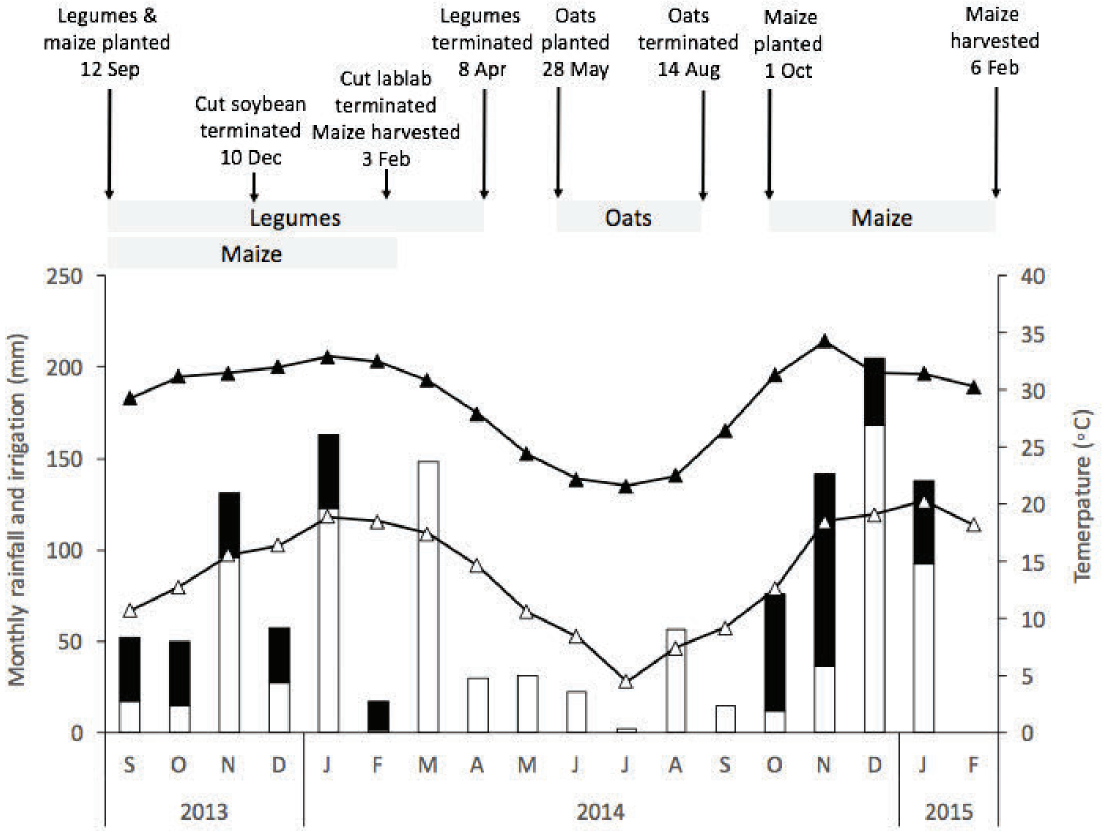

Figure 3.2. Monthly rainfall (white bars) and irrigation (black bars) and mean monthly maximum (solid triangles) and minimum (hollow triangles) temperature and key activities during the experiment (12 Sep 2013-6 Feb 2015).

3.3.3. Legume ley agronomic management

Legumes and the maize control were planted on 12 September 2013 with a no-till tyned cone seeder at recommended seeding rates and row spacing (Table 3.1). A basal application of single superphosphate (8.8% P, 11% S and 19% Ca) was applied prior to sowing. During legume cultivation, weeds were controlled with a pre-sowing application of glyphosate (450 g a.i./L) at 2 L/ha and a post-sowing pre-emergent application of imazethapyr (700 g a.i./kg) at 140 g/ha in the legume plots and pendimethalin (440 g a.i./L) at 3.4 L/ha in the maize plots. Legumes were inoculated with commercial strains of rhizobium with peat slurry (Nodulaid®, BASF).

Once the legumes were approaching peak biomass (early flowering), shoot biomass in cut subplots was cut to a height of 70 mm above ground level and removed from the plots. Where legumes regrew, shoot biomass was removed multiple times following the process described above. Shoot biomass was cut and removed three times for butterfly pea and burgundy bean (76, 144 and 208 days after sowing (DAS)) and twice for centro (119 and 208 DAS) and lablab (82 and 144 DAS). At termination, all replicate plots were sprayed with glyphosate (450 g a.i./L) at 2 L/ha and dicamba (500 g a.i./L) at 400 mL/ha. Two weeks after spraying, uncut subplots were mulched with a tractor mounted flail mower set at 100 mm above ground level.

Table 3.1. Details of cultivar, seeding rate (bare seed), row spacing and plant population of legume, oat and maize rotations.

Common name	Species	Cultivar	Inocu-lant	Seed rate (kg/ha)	Row space (m)	Plant population (plants/m^2)
Legume ley						
Butterfly pea	*Clitoria ternatea*	Milgara	CB756	15	0.33	17
Burgundy bean	*Macroptilium bracteatum*	Juanita & Cadarga	CB1717	8	0.33	18
Centro	*Centrosema pascuorum*	Cavalcade	CB1923	8.5	0.33	20
Lablab	*Lablab purpureus*	Highworth	CB1024	40	0.33	18
Soybean	*Glycine max*	Hayman	CB1809	65	0.33	20
Maize	*Zea mays*	PAC 735		38	0.66	6
Oat bioassay						
Oats	*Avena sativa*	Genie		60	0.33	NA
Maize bioassay						
Maize	*Zea mays*	PAC 735		45	0.66	6.5

NA, Not applicable

Each time legume biomass was cut and removed, biomass production was measured by collecting shoot biomass in three 0.25 m^2 quadrats (0.75 m^2) in each replicate legume plot. Maize grain and stover above the first node was harvested at maturity on 3 February from two adjacent 3 m lengths (4 m^2) of crop row in the centre of each plot. Maize grain and stover was also removed from the main plots to allow comparison to the legume subplots with biomass cut and removed and to also avoid confounding the

N response curve used to calculate fertiliser equivalence values. Legume biomass samples and a sub-sample of 6 maize plants from each replicate plot were dried at 80°C until constant mass was reached. These samples were used to determine dry matter (DM), stover production and tissue N content.

3.3.4. Bioassay oat and maize crops

After the legumes and maize control were terminated, an oat cover crop was sown in all replicate plots on 28 May 2014 to ensure even soil water at planting for the subsequent bioassay maize crop. Biomass cuts were taken for the oats from each replicate legume subplot and maize main plots at 78 DAS (14 August 2014) by collecting shoot material above 10 mm in two 0.5 m^2 quadrats and drying at 80°C until constant mass was reached. On the same day, the oat crop was terminated with glyphosate (450 g a.i./L) at 4 L/ha. Following termination, oat biomass was mulched on 3 September using a tractor mounted flail mower set at 100 mm above ground level.

After the oat crop was terminated and mulched, a bioassay maize crop was sown on 1 October 2014 across the experimental area. Basal nutrients were applied to ensure nutrients other than N were non-limiting. Following sowing, atrazine (900 g a.i./kg) at 2.5 L/ha, S-metolachlor (960 g a.i./L) at 2 L/ha and glyphosate (450 g a.i./L) at 3 L/ha were sprayed across the experiment. Broadleaf weeds including volunteer forage legumes were controlled in-crop with 2,4-D amine (625 g a.i./L present as dimethyllamine salt) at 1.5 L/ha. Supplementary irrigation of up to 25 mm was applied each week from two weeks after planting until anthesis to ensure cumulative rainfall and irrigation >25 mm/week.

At maize anthesis, biomass cuts and tissue N content were measured from three adjacent 0.75 m lengths of crop row (1.5 m^2) in each replicate sub-subplot by collecting shoot material above the first node and drying at 80°C until constant mass was reached. Maturity biomass, grain yield and ear number was measured from two adjacent 3 m lengths of crop row (4 m^2) in the centre of each sub-subplot. A sub-sample of six plants was dried at 80°C until constant mass was reached and then threshed to determine biomass, grain yield and kernel weight.

3.3.5. Measurement of plant N accumulation

For all biomass samples, a ground subsample was analysed for total N (mg N g^{-1}) using a calibrated Bruker^{TM} Near Infra-red Spectrometer. Total legume shoot biomass N for uncut subplots was measured using the N concentration for shoot material collected at maximum biomass (3 February), when total N was expected to be highest. This was calculated as:

Total shoot N retained = [(shoot DM at termination) x (shoot %N/100)] [1]

As root N is not accounted for in shoot biomass N calculations, total plant N for uncut legumes was calculated by multiplying shoot biomass N by a root factor to estimate the additional below-ground plant N. As the impact of cutting on below ground N remains unclear (Unkovich et al. 2010), cut legume total plant N was calculated using below ground N from uncut legumes.

Total uncut plant N retained = [(Total shoot N retained) x (root factor)] [2]

Total cut plant N retained = [(Total uncut plant N retained) – (Total uncut shoot N retained)] + [Total shoot cut N retained] [3]

The root factors used were 1.8 for butterfly pea and burgundy bean based on the mean value determined across a range of perennial pasture legumes (45% below ground N; Peoples et al. (2012)), 1.49 for centro and lablab assuming partitioning of total plant N was similar to other annual legumes (33% below ground N; Unkovich et al. (2010)), 1.61 for soybeans (38% below ground N; Unkovich et al. (2010)), 1.85 for oats (46% below ground N) and 1.58 for maize, based on mean below ground N of a range of temperate cereals (37% below ground N; Wichern et al. (2008)).

3.3.6. Measurement of available soil N and water

Soil nitrate (NO_3-) concentrations and soil water content were measured four weeks prior to starting the experiment; there was 4 mm of rain between soil sampling and legume planting. Soil nitrate and water content were also measured in each replicate plot following the legume and oat crops and after the maize crop in plots with no N fertiliser applied. For each subplot or sub-subplot, soil samples were collected to a depth of 1.2 m for NO_3- and 1.5 m for water content. Samples were separated into 0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60, 0.60-0.90, 0.90-1.20 and 1.20-1.50 m layers, with subsamples removed for NO_3- and gravimetric water content analysis. For gravimetric water content, each sample was weighed immediately, dried in the oven at 105°C for ≥ 3 days and then reweighed. Volumetric soil water content was calculated using bulk densities for a soil that had previously been characterised for the experimental site for the APSoil database, this was soil Lawes No037 (Dalgliesh et al. 2012). NO_3- was analysed at a commercial laboratory following drying at 40°C for ≥ 3 days using a 1:5 soil:water extraction (Rayment and Lyons 2011). Total soil N was calculated using bulk densities described above (APSoil, soil Lawes No037). Field soil N results are only presented for 0-0.45 m, as >92% of NO_3- was above 0.45 m. In-crop mineralisation was calculated using maize total plant N and soil N pre and post maize.

3.3.7. Statistical analysis

Analysis of variance in Genstat 16.1 (VSV International Ltd. Hemel Hempstead, UK) was used to determine statistical differences in soil N and water content, legume N concentration and maize production. Mean separation was tested using least significant difference (l.s.d) at *P*<0.05. Fertiliser equivalence values were determined using linear regression and analysis of variance. All data was normally distributed and not subject to transformation.

3.4. Results

3.4.1. Legume N inputs

At legume termination residual shoot N was higher after uncut legumes (313 kg N/ha) than cut legumes (38 kg N/ha) (*P*<0.001). When shoot biomass was retained, butterfly pea total plant N was at least 150 kg N/ha higher than other uncut forages, however, when biomass was removed, total plant N retained for butterfly pea did not differ significantly from cut centro or burgundy bean (Table 3.2). Differences in total plant N retained were largely driven by the difference in root factors used for perennial (1.8; 45% below ground N) and annual forage legumes (1.49; 33% below ground N). Shoot N concentration ranged from 2.08-3.32 % across all treatments. For uncut legumes, shoot N concentration for butterfly pea (2.88%) and soybean (3.02%) was similar to centro (2.56%) but significantly higher than burgundy bean (2.37%) and lablab (2.31%) (*P*<0.001).

Table 3.2. Measured shoot N and estimated total plant N retained for maize or forage legumes where shoot biomass was either retained (uncut) or removed (cut). Mean ± standard error (brackets). Different letters indicate statistically significant (*P*<0.05) differences between species and shoot biomass management.

Crop	Shoot N retained (kg N/ha)			Total plant N retained (kg N/ha)[A]		
Maize	5	(2)	c	106	(40)	g
Uncut legumes						
Butterfly pea	346	(55)	ab	623	(100)	a
Centro	315	(15)	b	469	(22)	bc
Lablab	264	(21)	b	393	(31)	cd
Burgundy bean	259	(26)	b	466	(47)	bc
Soybean	374	(49)	a	601	(79)	ab
Cut legumes						
Butterfly pea	50	(10)	c	329	(54)	cde
Centro	40	(10)	c	193	(16)	efg
Lablab	36	(3)	c	155	(7)	fg
Burgundy bean	37	(5)	c	240	(25)	def
Soybean	33	(9)	c	260	(30)	def

[A] Adjusted to include below ground plant N using root factors, below ground N for cut legumes was assumed to be the same as uncut legumes

3.4.2. Field soil N and water

Soil N was 18 kg N-NO_3/ha at legume planting and 16 kg N-NO_3/ha at oat planting; there was no difference between treatments at oat planting. At oat cover crop termination, oat biomass contained 44 kg N/ha following uncut legumes, 33 kg N/ha following cut legumes and 44 kg N/ha following maize (P=0.09). Oat below ground plant N was estimated at 38 kg N/ha for uncut legumes, 28 kg N/ha for cut legumes and 37 kg N/ha for maize.

At planting of the maize bioassay, soil N for the uncut legumes (59 kg N/ha) was higher than for the cut legumes (19 kg N/ha) and the maize control (20 kg N/ha) (P<0.001, Table 3.3). During the maize bioassay, additional N mineralized following uncut butterfly pea (169 kg N/ha), centro (129 kg N/ha) and soybean (91 kg N/ha) compared to the maize control (P<0.001) (Table 3.3). Cut butterfly pea and centro also increased N mineralisation, with an additional 70 kg N/ha mineralized for cut butterfly pea (P<0.001) and 47 kg N/ha for cut centro (P=0.15). At maize harvest an additional 15-26 kg N/ha remained following uncut butterfly pea and centro. Soil water was 289 mm at oat planting and 245 mm at maize planting (0-0.9 m); soil water was similar for all treatments at maize planting (P=0.51).

Table 3.3. Soil N-NO_3^- (0-0.45 m) at planting and harvest of the subsequent maize bioassay crop, and in-crop mineralisation for the maize bioassay following either a maize control or forage legumes where shoot biomass was either retained (uncut) or removed (cut). Mean ± standard error (brackets). Different letters indicate statistically significant ($P<0.05$) differences between species and shoot biomass management.

Previous crop	Soil N maize planting (kg N/ha)	Soil N maize harvest (kg N/ha)	In-crop mineralisation (kg N/ha)
Maize	20 (6) ^{de}	11 (3) ^{c}	120 (30) ^{ef}
Uncut legumes			
Butterfly pea	73 (3) ^{a}	36 (14) ^{a}	289 (31) ^{a}
Centro	33 (3) ^{bc}	25 (8) ^{ab}	249 (17) ^{ab}
Lablab	40 (9) ^{b}	14 (2) ^{bc}	197 (17) ^{bce}
Burgundy bean	31 (4) ^{bc}	10 (3) ^{c}	140 (16) ^{cdef}
Soybean	67 (9) ^{a}	13 (3) ^{bc}	211 (20) ^{bc}
Cut legumes			
Butterfly pea	22 (2) ^{cde}	18 (4) ^{bc}	190 (18) ^{bcd}
Centro	24 (2) ^{cd}	14 (2) ^{bc}	167 (19) ^{cde}
Lablab	13 (3) ^{e}	8 (2) ^{c}	103 (13) ^{f}
Burgundy bean	19 (4) ^{de}	8 (2) ^{c}	129 (29) ^{def}
Soybean	18 (2) ^{de}	8 (3) ^{c}	126 (31) ^{def}

3.4.3. Legume effects on maize production and N uptake

Maize shoot N concentration at anthesis following uncut legumes was 0.2 % higher than after cut legumes (*P*<0.001, Table 3.4). This equated to maize accumulating an additional 60 kg N/ha of shoot N and 95 kg N/ha of total plant N when legume shoot biomass was retained rather than cut and removed. Maize N uptake after uncut legumes varied between species; an additional 197 kg N/ha total plant N was accumulated after butterfly pea, 136 kg N/ha for soybean, 128 kg N/ha for centro, 94 kg N/ha for lablab, while burgundy bean failed to increase N uptake above control levels (*P*<0.001). When legume shoot biomass was cut and removed, no legumes significantly increased maize N uptake above control levels, although N uptake after cut centro and cut butterfly pea was similar to N uptake after uncut centro. Maize anthesis biomass showed a similar trend. Uncut butterfly pea, centro and soybean increased maize anthesis biomass by 2.3-4.1 t/ha compared to the maize control, while uncut lablab and burgundy bean failed to increase biomass above control levels (*P*<0.01). No cut legumes increased anthesis biomass above control levels.

Table 3.4. Dry matter (DM), shoot N concentration, accumulated shoot N and total accumulated plant N at anthesis for the unfertilised maize bioassay crop following either a maize control or forage legumes where shoot biomass was retained (uncut) or removed (cut). Mean ± standard error (brackets). Different letters indicate statistically significant (*P*<0.05) differences between species and shoot biomass management;n.s.,not significant(P>0.05); n.d.,not determined. ^{A}Adjusted to include below ground N using root factors

Previous crop	Accumulated anthesis DM (t DM/ha)	Shoot N concentration (%)$^{N.S}$	Accumulated shoot N (kg N/ha)	Accumulated plant N^{A} (kg N/ha)	Additional N accumulated (kg N/ha)	Legume N recovered (%)
Maize	5.0 (1.7) ^{de}	1.7 (0.2)	82 (25) ^{de}	129 (40) ^{de}	n.d.	n.d.
Uncut legumes						
Butterfly pea	9.1 (1.1) ^{a}	2.3 (0.2)	207 (25) ^{a}	326 (39) ^{a}	197	32
Centro	7.8 (0.1) ^{abc}	2.0 (0.1)	162 (2) ^{ab}	257 (3) ^{ab}	128	26
Lablab	7.3 (0.7) ^{abcd}	2.0 (0.2)	141 (11) ^{bc}	223 (17) ^{bc}	94	23
Burgundy bean	5.9 (0.2) ^{cd}	1.7 (0.2)	101 (15) ^{cde}	160 (23) ^{cde}	31	13
Soybean	8.8 (0.6) ^{ab}	1.9 (0.1)	168 (16) ^{ab}	265 (25) ^{ab}	136	23
Cut legumes						
Butterfly pea	6.4 (0.2) ^{bcde}	1.9 (0.1)	123 (25) ^{bcd}	194 (14) ^{bcd}	65	20
Centro	6.5 (0.3) ^{bcde}	1.7 (0.1)	112 (11) ^{cde}	177 (17) ^{cde}	48	25
Lablab	4.2 (0.9) ^{e}	1.7 (0.1)	67 (8) ^{e}	108 (13) ^{e}	0	0
Burgundy bean	5.2 (0.9) ^{de}	1.7 (0.2)	89 (21) ^{de}	140 (33) ^{de}	11	5
Soybean	4.6 (0.7) ^{e}	1.9 (0.1)	86 (14) ^{de}	136 (23) ^{de}	7	3

Maize grain yield was highest following uncut butterfly pea (10.9 t/ha), lablab (9.2 t/ha), centro (8.8 t/ha), and soybean (8.2 t/ha) ($P<0.01$, Table 3.5). For these species, retaining instead of cutting and removing biomass increased maize crop grain yield from 2.4-4.9 t/ha to 8.2-10.9 t/ha and harvest index from 0.29-0.39 to 0.47-0.50 ($P<0.001$). In comparison, uncut burgundy bean failed to increase maize yield above control levels. Cut legumes did not increase grain yield above control levels, however the dry matter production and harvest index of the uncut and cut centro and cut butterfly pea were similar.

Differences in grain yield were mainly driven by kernel weight per ear, which doubled when legume biomass was retained rather than cut and removed ($P<0.001$). Consequently, for centro, butterfly pea, lablab and soybean, kernel weight per ear accounted for ≥80% of the difference in grain yields between cut and uncut treatments. The number of ears per hectare was 17% higher for uncut legumes (69,444 ears/ha) compared to cut legumes (59,259 ears/ha) ($P<0.01$). This equated to <1 ear per plant for cut legumes and >1 ear per plant for uncut legumes.

Table 3.5. Maize stover, ears per m^2, kernel weight per ear, grain yield and harvest index for an unfertilised maize bioassay crop following either a maize control or forage legumes where shoot biomass was retained (uncut) or removed (cut). Mean ± standard error (brackets). Different letters indicate statistically significant ($P<0.05$) differences between species and shoot biomass management; n.s., not significant ($P>0.05$)

Previous crop	Grain yield (t/ha)	Ear number (ears/m^2)$^{n.s.}$	Kernel weight per ear (g)	Stover (t DM/ha)	Harvest index
Maize	3.0 (1.1) ^{c}	5.8	55 (24) ^{b}	5.8 (0.9) ^{d}	0.33 (0.06) ^{c}
Uncut legumes					
Butterfly pea	10.9 (0.7) ^{a}	8.0	147 (6) ^{a}	10.9 (0.8) ^{a}	0.50 (0.01) ^{a}
Centro	8.8 (0.8) ^{ab}	6.4	149 (7) ^{a}	9.9 (1.3) ^{ab}	0.47 (0.02) ^{ab}
Lablab	9.2 (0.7) ^{ab}	7.8	133 (9) ^{a}	9.1 (0.6) ^{abc}	0.50 (0.03) ^{a}
Burgundy bean	4.5 (1.5) ^{c}	7.6	70 (23) ^{b}	6.3 (1.5) ^{cd}	0.39 (0.04) ^{bc}
Soybean	8.2 (0.6) ^{b}	6.7	130 (7) ^{a}	9.4 (1.4) ^{ab}	0.47 (0.03) ^{ab}
Cut legumes					
Butterfly pea	3.5 (0.5) ^{c}	6.0	65 (7) ^{b}	6.4 (0.2) ^{cd}	0.32 (0.04) ^{c}
Centro	4.9 (0.5) ^{c}	6.0	82 (16) ^{b}	7.5 (0.3) ^{bcd}	0.39 (0.03) ^{bc}
Lablab	3.3 (1.5) ^{c}	5.9	61 (16) ^{b}	5.7 (1.7) ^{d}	0.33 (0.04) ^{c}
Burgundy bean	3.4 (1.0) ^{c}	6.6	54 (11) ^{b}	6.6 (0.9) ^{cd}	0.32 (0.03) ^{c}
Soybean	2.4 (0.4) ^{c}	5.6	49 (16) ^{b}	5.7 (0.4) ^{d}	0.29 (0.02) ^{c}

3.4.4. Legume fertiliser equivalence value

The N fertiliser equivalence value varied between legumes. Maize yield following uncut butterfly pea, centro, lablab and soybean was equivalent to continuous cereal cropping (maize-oats-maize) provided with 100-150 kg urea-N/ha (Figure 3.3). In contrast, uncut burgundy bean failed to contribute large amounts of N. As with the responses to legumes, these yield responses were related to kernel weight per ear. The addition of fertilizer N had no effect on maize kernel weight following the uncut legumes (butterfly pea, centro, lablab and soybean). However, the addition of N fertiliser increased kernel weight per ear from 54-55 g/ear (0 kg urea-N/ha) to 145-147 g/ear (150 kg N/ha) for burgundy bean and the continual cereal cropping. Cobs per hectare was similar for all treatments (P=0.79).

Centro was the only legume when shoot biomass was cut and removed where contributions of N to maize yield and kernel weight per ear were detected. For the other legumes when shoot biomass was removed, maize yield and kernel weight per ear were equivalent to the control for all N fertiliser rates. Consequently, with the exception of centro, 100 kg urea-N/ha was required to alleviate the yield penalty imposed by removing N within the cut legume biomass.

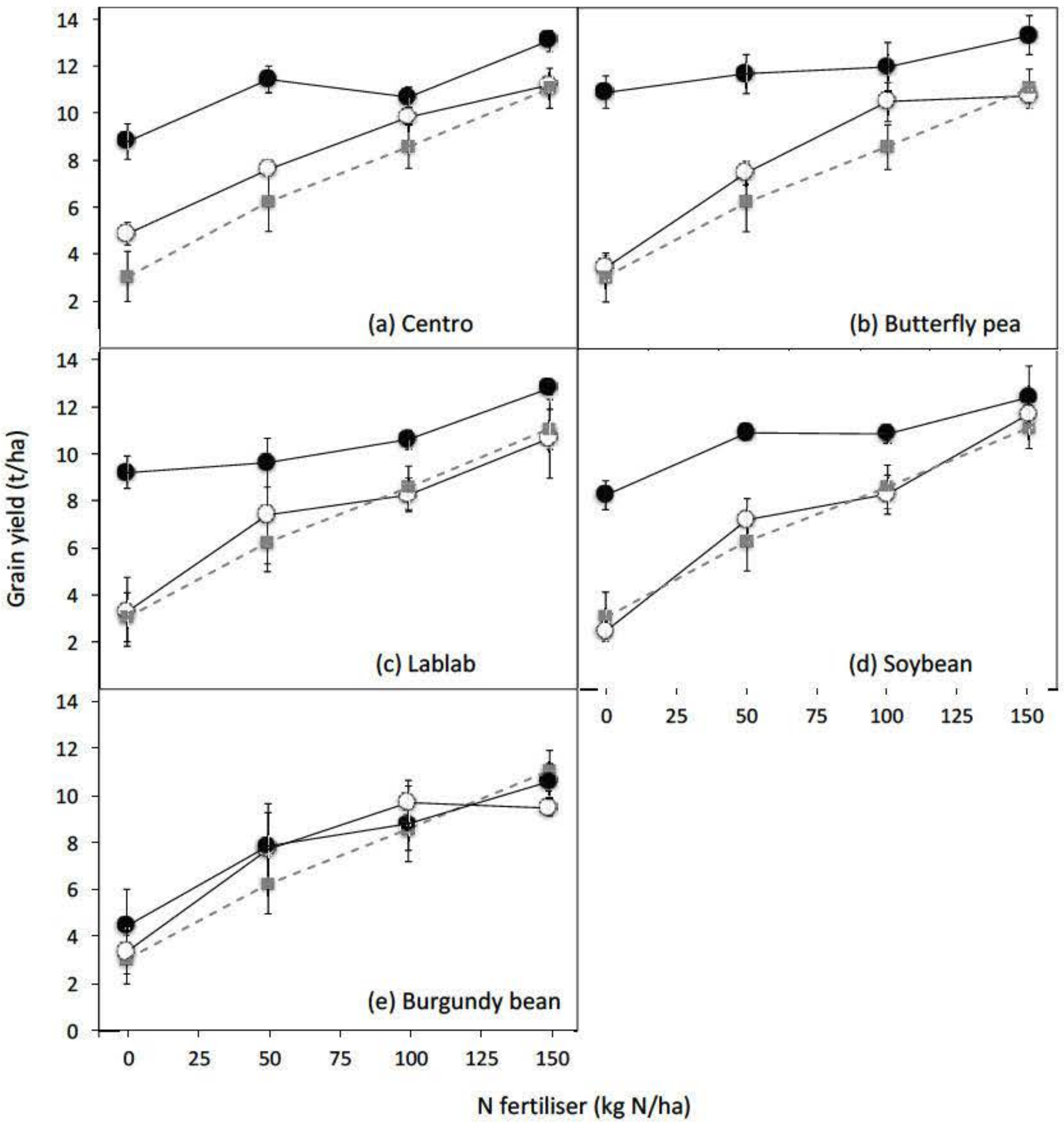

Figure 3.3. Maize grain yield in response to applications of urea-N at sowing following forage legumes when shoot biomass was either retained (solid circle) or removed (hollow circle) compared with following a maize control (grey square). Mean ± standard error.

Linear regression indicated that uncut butterfly pea, centro, soybean and lablab provided the most N (*P*<0.05), contributing equivalent to 99-153 kg urea-N/ha (Table 3.6). Uncut burgundy bean contributed equivalent to only 25 kg urea-N/ha. In comparison, cut centro fertiliser equivalence was 33 kg urea-N/ha, although an additional 100 kg urea-N/ha was required to maximise maize yield. Consequently, for centro, removing shoot biomass reduced the fertiliser equivalence value by 77%. The penalty was larger for other legumes, as cutting removed any N fertiliser benefit. Importantly, the fertiliser substitution value was highly variable for all treatments, with standard errors up to 42.

Table 3.6. Estimated N fertiliser equivalents (kg urea-N/ha) required to achieve similar grain yield for a maize crop following forage legumes where shoot biomass was either retained (uncut) or removed (cut). Mean ± standard error (brackets). Linear regression; maize grain yield (t/ha) = 0.05*(x kg N/ha) + 3.27, $R^2=0.99$

Legume	Shoot biomass management	
	Removed	*Retained*
Butterfly pea	5 (3)	153 (42)
Lablab	0	118 (40)
Centro	33 (11)	111 (36)
Soybean	0	99 (34)
Burgundy bean	0	25 (21)

3.5. Discussion

This paper reports that tropical forage legumes can contribute equivalent to >100 kg urea-N/ha and triple grain yield of a subsequent maize crop. This probably represents the upper potential for legume N inputs and recovery of legume N, as irrigation enabled high legume productivity, rapid residue decomposition and high maize N demand. We found that the penalty of removing fodder is large, with no significant increase in subsequent grain yield. When shoot biomass was retained centro, butterfly pea and lablab had the largest yield benefit, and centro was the only species with a discernible N contribution once shoot biomass was removed.

3.5.1. The impact of forage legumes on subsequent grain yield

A key role of forage legumes in cropping systems is their ability to improve grain yield and quality of subsequent cereal crops (Giller 2001). In this experiment, when shoot biomass was retained butterfly pea, lablab and centro increased maize grain yield by 7.9, 6.2 and 5.8 t/ha, respectively, compared to a maize control. Although such substantial yield increases are achievable under irrigation, for dryland conditions reported relative yield increases commonly range from 0.3-5 t/ha (Armstrong et al. 1999b; Peoples and Herridge 1990; Sileshi et al. 2008). In part, this is driven by low inputs of fixed N under dryland conditions (<50 kg shoot fixed-N/ha) compared to irrigated systems (120 kg shoot fixed-N/ha) (Peoples et al. 2012; Rochester et al. 2001). However, relative yield increases also depend on initial soil fertility and the N demand of the subsequent crop, which is largely driven by rainfall and crop type (Giller 2001). Thus, this research indicates that the potential impact of these species on subsequent crop yield is at least double that commonly achieved under dryland conditions, with the most promising species – butterfly pea, centro and lablab – potentially tripling grain yield under non-water limiting conditions.

Importantly, in the common environment of this experiment, not all species increased subsequent grain yield to the same degree. Burgundy bean failed to increase maize yield even when shoot material was retained. Thus, there isn't a consistent relationship between legume biomass or N inputs and the impact on subsequent crop yield (Armstrong et al. 1999b). This lack of response may be because above ground burgundy bean residues were observed to break down slowly compared to other species. This may be due to high lignin or polyphenol contents (Fillery 2001; Tian and Kang 1998), as burgundy bean leaf N concentration (2.37 %) favoured mineralisation (Peoples and Herridge 1990). While, Bell. *et al* (2017) found that burgundy bean commonly accumulated less plant N than lablab, in other experiments burgundy bean has increased both soil N and subsequent crop yield (Armstrong et al. 1997; Whitbread et al. 2005). Consequently, the potential impact of forage legumes on subsequent crop production differs with species and environmental conditions.

High and sustained returns from livestock means commercial and smallholder farmers often preferentially allocate legume residues to livestock (Giller et al. 2009; Shelton et al. 2005). However, declining soil fertility and increased N costs increase the value of achieving dual fodder-soil N benefits (Bell et al. 2012; Whitbread et al. 2009; White et al. 2013). These dual benefits were not achieved in this experiment, as when legumes were cut and removed they failed to significantly increase maize growth or grain yield. Similar yield penalties from forage removal have also been found in Zimbabwe and Brazil (Smyth et al. 1991; Whitbread et al. 2004). Yet, in southern Queensland, lablab with biomass cut and removed increased subsequent grain sorghum yield in 2010-11 by 50% at one site, while there was no yield response at another site (Bell et al. 2017). In the same set of experiments, there was no yield response following burgundy bean (Bell *et al*. 2017), demonstrating that fodder-soil N benefits vary with legume species and environmental conditions. Although N transfer in animal excreta in cut and carry systems may increase crop yield responses (Giller 2001), high labour requirements often prohibit the use of excreta as a soil amendment (Bayu et al. 2005). As a result, where dual fodder-soil N benefits are sought, removing shoot biomass once, retaining a higher proportion of shoot biomass or grazing are options which may increase legume N contributions and grain yield responses (Peoples et al. 2012).

3.5.2. Fertiliser equivalence values

Estimating the fertiliser equivalence provided by legumes provides a useful mechanism to quantify their value in a farming system. Fertiliser equivalence values when legume fodder is cut and removed provide the best estimates for the N benefits that could be achieved in smallholder cut and carry systems (Oikeh et al. 1998). For this study, only centro could substitute urea when cut, contributing equivalent to 33 kg urea-N/ha. This value is similar to verano (*Stylosanthes hamata*) in northern Australia which, when used for hay, contributed 21 kg N/ha to the following maize crop (Jones et al. 1996). The N inputs from cut centro, and also butterfly pea, appeared to increase biomass accumulation and maintain ear number however, there was insufficient N to increase grain weight. Thus, removing centro and butterfly pea shoot biomass had a larger penalty for maize grain yield than biomass production, indicating that additional fertilizer N is required to increase grain yield when shoot biomass is cut and removed.

Here we estimated N equivalence values provided by legumes with biomass retained of >100 kg fertiliser-N/ha. While values of 30-90 kg fertiliser-N/ha are more common (Dimes et al. 1996; Njarui and Mureithi 2010; Peoples and Craswell 1992; Peoples et al. 1995), high fertiliser equivalents were anticipated in this experiment because irrigation enabled high legume and maize productivity, high maize N demand and soil conditions that allowed for rapid residue decomposition and mineralisation. Therefore, these fertiliser equivalence values probably represent the upper potential for legume N inputs and recovery of legume residue N. Lower fertiliser equivalence values would be expected under dry land conditions because drier soil conditions would decrease legume productivity and N inputs as well as subsequent residue decomposition and mineralisation rates. The legume rotation could also increase moisture stress in the subsequent cereal crop, reducing N uptake and subsequent yield (Armstrong et al. 1999b). Therefore, large fertiliser equivalents are achievable when legume shoot biomass is retained but species selection, management and environmental conditions determine whether they are realised.

Managing variable legume N inputs and synchronising N release to crop N uptake are key aspects of maximizing fertiliser equivalence values. In this experiment, legume N inputs and fertiliser equivalents were highly variable. Such variability commonly persists between years and sites, with cereal grain yields more variable following a legume rather than a fertiliser treatment (Becker et al. 1995). This variability makes it difficult to estimate top-up fertiliser requirements and the economic value of forage legumes (Becker et al. 1995). Additionally, the management of N release from legume residues to meet peaks in crop N demand and minimize N losses is another major challenge, particularly for tropical farming systems (Crews and Peoples 2005; Giller

2001). In this experiment, the oat cover crop potentially affected N synchrony by immobilising and conserving available N in an organic form (Crews and Peoples 2005), however differences in oat cover crop N uptake and soil N at oat crop termination were small. Consequently, maize yield was mainly driven by in-crop mineralisation rather than soil N at planting.

3.5.3. Maize N uptake

Maize N uptake and accumulation of legume derived N reflect fertiliser equivalence values. After butterfly pea, centro and lablab with shoot biomass retained, maize accumulated 94-197 kg N/ha of additional N, which equates to maize accumulating 8-16 kg N/ha of legume derived N for each ton of legume shoot dry matter retained. Although cut legumes didn't significantly increase maize N uptake, results indicate that cut centro and butterfly pea may be able increase maize N uptake by 48-65 kg N/ha. Consequently, for legumes with shoot biomass retained and butterfly and centro with shoot biomass removed, maize recovered 23-32% of legume total plant N, which is at the upper end of the reported range of 10-30% (Fillery 2001; Giller and Cadisch 1995; Peoples et al. 2009). In comparison, water limited crops or crops after short fallows or mature legume residues may accumulate <10% of legume plant N (Armstrong et al. 1998; Fillery 2001; Peoples et al. 2009). It is also likely that an N sparing effect contributed to increased crop productivity (Armstrong et al. 1997). Thus, under non-water limiting conditions, the maximum amount of legume derived N accumulated by the subsequent crop was 32%.

Total below ground legume N and the rate of N turn over for subsequent cereal crops has not been widely studied for tropical forage legumes under different management strategies (Fillery 2001; Unkovich et al. 2010). In this study, below ground and senesced residue N from cut legumes contributed minimal amounts of N to the subsequent crop, with only cut centro and butterfly pea contributing measurable amounts of additional N (maize accumulated an additional 48-65 kg N/ha). It remains unclear whether this low N contribution is due to a decrease in total below ground N, slower N turn over or both. Below ground legume N was estimated at 154-277 kg N/ha, however it remains unclear whether these root factors (Peoples et al. 2012; Unkovich et al. 2010), which were determined across a range of pasture legumes, are suitable. Thus, further research is required to determine whether estimates for below ground legume N (33-45%) (Peoples et al. 2012; Unkovich et al. 2010) and recovery of below ground residue N (18-25%) (McNeill et al. 1997) apply for annual and perennial tropical forage species.

3.5.4. Conclusion

This study demonstrates that tropical forage legumes can provide large N inputs and yield benefits to the subsequent crop when their growth is maximised and subsequent crop N demand is high. Although these N benefits are reduced under conditions with limited water or other constraints to growth, this study greatly contributes to our understanding of the upper potential of key tropical forage legumes. We found that legume biomass removal, that occurs in hay production or cut and carry systems, greatly reduces the N benefit to the subsequent crop. Hence, there is a large trade-off between maximising the use of biomass for livestock fodder and translating legume N benefits to the subsequent cereal crop. Such trade-offs may be mitigated where excreta is applied to crops, under grazing or where greater residual biomass is retained and returned to the soil. We also found there were significant differences between tropical legume species in their potential to produce N for the subsequent crop. When shoot biomass was retained centro, butterfly pea and lablab provided the greatest benefit, while burgundy bean provided little, if any, benefit. Where biomass was cut and removed, centro was the only legume that provided an N benefit to the subsequent crop. Given this, further research is required to understand how tropical forage legume species and their management affects above and below ground legume residue N, legume N turn-over and the resulting production impacts. In conclusion, tropical forage legumes can provide large N inputs, however achieving substantial increases in subsequent crop production requires selection of suitable legume species, retention of legume shoot biomass and environmental conditions which maximise legume and crop productivity.

3.6. Acknowledgements

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University of New England

STATEMENT OF ORIGINALITY

We, the Research PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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4. Simulating maize yield response to a previous forage legume (*Clitoria ternatea*) rotation in West Timor, Indonesia

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4.1. Abstract

In smallholder farming systems, declining soil fertility and low nitrogen (N) inputs contribute to low yields for staple crops such as maize. Forage legumes offer an alternative, 'free', source of N which can help address these yield gaps. We simulated the impact of forage legume butterfly pea (*Clitoria ternatea*) biomass on subsequent maize production in West Timor, Indonesia, a region where both N inputs and food self-sufficiency are low. The impact of legume biomass production and management (retain vs. remove shoot biomass) on subsequent maize yield was simulated for three maize densities (2, 4 and 6 plants/m^2) for six case study farms with different agro-climatic conditions. The impact of weed control on yield benefits was also simulated. The simulations indicated that, while forage legumes can increase maize grain yield across a range of agro-climatic zones, there was little or no benefit when shoot biomass was removed or when weed control was poor. Simulated yield responses also depended on maize plant density, with little benefit at 2 plants/m^2 compared to increases in maize yield of up to 3.5 t/ha for 4 and 6 plants/m^2. Thus, while forage legumes can provide large N benefits, to realise the yield benefits on smallholder farms, suitable forage legume management and improved maize agronomic practices are required.

Additional keywords: rotation, herbaceous, green-manure, grain yield, smallholder, tropical

4.2. Introduction

Large yield gaps for maize in developing countries indicate that significant yield gains are achievable with the use of appropriate technologies (Tilman et al. 2002). In Southeast Asia, the gap between yield potential – this highest yield achievable on-farm with appropriate levels of nutrients, water and weed control – relative to current on-farm yield range from 3.1 to 4.4 t/ha, indicating there is significant scope to increase maize production (Pingali and Pandy 2001). These large differences between yield potential and current yield are, in part, due to a range of biophysical factors including low or declining soil fertility, low adoption of improved varieties (open pollinated and hybrid), drought, disease, insects and weeds (Gerpacio and Pingali 2007; Pingali and Pandy 2001). Of the abiotic constraints, low soil fertility resulting from soil erosion, reduced fallow periods and expansion into marginal lands is a significant constraint to maize production (Gerpacio and Pingali 2007). While Gerpacio and Pingali (2007) reported that subsistence farmers in Asia address soil fertility constraints by applying a wide range of N fertiliser rates (9-382 kg fertiliser-N/ha) to their maize, there are regions where additional N – organic or synthetic – is not applied (Hosang 2014). This variation in N inputs is particularly important in Eastern Indonesia where the staple crop maize receives little or no N inputs and high levels food insecurity persist (FAO et al. 2010; Hosang 2014).

In wealthier regions of Indonesia, maize commonly receives 72-104 kg N/ha (Swastika et al. 2004), however East Nusa Tenggara (ENT) province, only 13% of maize crops are fertilized, commonly receiving <58 kg N/ha (Hosang 2014; World Food Program 2009). These low N inputs is particularly important given <30% of households in ENT are food secure (FAO et al. 2010). Although not extensively studied in ENT, in other regions of Indonesia there are a range of factors which commonly contribute to low levels of fertiliser application including financial cost and access to cash or credit (FAO et al. 2010); lack of markets, market access and infrastructure (Gregory et al. 2010); inappropriate agronomic recommendations (Ngongo 2011) and poor government policy (Osorio et al. 2011). Importantly, organic N inputs, such as manure, are also low because labour inputs are commonly too high to transfer manure from where livestock are tethered to crop land, manure is instead used for vegetable crops (Ngongo 2011). Thus, there is considerable scope to increase maize production and food self-sufficiency in ENT by increasing N inputs for maize crops.

Forage legumes offer an alternative source of N, with biological N fixation providing a 'free' source of N for agriculture (Giller and Cadisch 1995). Previous research in West Timor, ENT, has shown that butterfly pea (*Clitoria ternatea*) suits a range of agro-climatic conditions identified in West Timor and can increase maize grain yield by 0.2-2.7 t/ha when biomass is retained on the field (Dalgliesh et al. 2010; Nulik et al. 2013). While such increases in grain yield may contribute to household food self-sufficiency, the performance of forage legumes and the impact on subsequent maize yield is not well understood for the range of agro-climatic conditions experienced in West Timor. Understanding how soil and climate affect maize response to legume N is particularly important given the variability in yield responses reported for field experiments (Dalgliesh et al. 2010; Nulik et al. 2013). In addition, understanding the maize yield response when legume shoot biomass is removed is important, as farmers commonly favour using biomass for livestock production rather than to increase soil fertility (Chapter 6, Giller et al. 2009). This often results in no or very small increases in subsequent grain yield, removing any benefit to food self-sufficiency provided by the forage legumes (Chapter 2 and 3, Dalgliesh et al. 2010, Smyth et al. 1991). Thus, to quantify the potential impact of legume N on maize yield, the impact of legume biomass management on maize production for a range of agro-climatic zones needs to be better understood.

Importantly, reports by Dalgliesh et al. (2010) and Nulik et al. (2013) are for controlled experiments with an improved open-pollinated maize variety. Thus, reported yield benefits are likely to exceed what will be achieved on-farm given farmers commonly grow landrace varieties (Hosang 2014) and tend to weed late and over a long period (Ngongo 2011). This indicates that weed control is a key constraint which is likely to reduce the N benefit received by the maize crop. Such a delay in weeding is driven by both a lack of labour and high herbicide prices (0.09-0.1 M Rp/L glyphosate) (Ngongo 2011). Thus, even if N inputs are increased, if this isn't combined with appropriate agronomic practice then the N benefit is diminished. Thus, understanding how maize management interacts with the likely benefits of legume N is critical to understanding what benefits may be achievable on-farm.

Previous research has demonstrated that farming systems models are an effective tool for assessing the impact of crop management and forage legume rotations on smallholder crop production (Carberry et al. 2004; Robertson et al. 2005; Whitbread et al. 2010). For cropping systems in Asia, Gaydon et al. (2017) indicated that farming systems model APSIM (Holzworth et al. 2014) performed well, with simulations of major crops within the bounds of experimental error. Consequently, APSIM was used to simulate forage legume production and the impact of legume N on subsequent maize yield for a range of agro-climatic conditions in West Timor, Indonesia. To understand the likelihood of achieving these yield increases on-farm, the impact legume biomass management (retained vs. removed), maize plant density and weed management on yield responses were also simulated.

4.3. Methods

4.3.1. Research design

This study used farming system model APSIM (Holzworth et al. 2014) to simulate the range of butterfly pea production and subsequent maize yield responses that may be achieved on smallholder farms with different soil and climatic conditions. Soil and climate for six case study farms were parameterized based on existing data and soil chemistry analysis. Then, using information from a questionnaire assessing crop management, baseline maize production was simulated using farmers' current agronomic practices. Forage legume production was then simulated to determine the range of legume biomass production for a number of management and agro-climatic conditions. While results indicated that butterfly pea could produce 1-13 t/ha of total forage biomass, on-farm production in smallholder systems is likely to be much lower (up to 60% of potential yield, see Chapter 5) and thus farmers are more likely to produce 1-6 t/ha (Nulik et al. 2013). Consequently, simulations assessed the impact of different forage legume production levels (1-6 t DM/ha) on subsequent maize yield and how biomass management (retained vs. removed) affected yield responses. The impacts of maize plant density (2, 4 and 6 plants/m^2) and weed control were also simulated to determine how crop management affected yield benefits.

4.3.2. Site selection

To test the agronomic performance of butterfly pea and the impact on subsequent maize yield for a range of agro-climatic conditions, six villages were selected across lowland (0-300 m above sea level (ASL)), midland (300-600 m ASL) and highland regions (>600 m ASL) of West Timor, Indonesia. The sites at each elevation were primarily selected based on high cattle ownership and fodder constraints (Chapters 5 and 6), the range of sites also provided six different combinations of soil and climatic conditions which could be used to assess forage legume production and N benefits. Lowland villages selected were Uel and Manulai 1 (referred to as Manulai), midland villages were Ekateta and Camplong 2 (referred to as Camplong) and highland villages were Oenai and Kesetnana (Table 4.1). At each village, one farm was selected as a representative case study to assess the impact of forage legumes on crop production (see below), as well as livestock production and whole farm income (Chapter 5).

Table 4.1. Case study site characteristics for six farms in West Timor, Indonesia.

Farm	Altitude (m ASL)	Longitude	Latitude	Soil type^A for simulations	Soil PAWC^B (mm)	
					Maize	Butterfly pea
Lowland						
Uel	17	123°50'42"E	10°02'57"S	Inceptosol	165	222
Manuali	260	123°33'48"E	10°14'17"S	Vertosol	132	210
Midland						
Ekateta	422	123°55'59"E	09°58'32"S	Shallow Alfisol	88	164
Camplong	437	123°58'49"E	10°00'58"S	Alfisol	105	194
Highland						
Oenai	732	124°31'12"E	9°50'58"S	Alfisol	105	194
Kesetnana	771	124°14'56"E	9°51'42"S	Vertosol	132	210

[A] Derived from APSoil data base (Dalgliesh et al. 2012)

[B] PAWC; plant available water capacity

4.3.3. APSIM climate and soil parameterization

Baseline maize and forage legume production and the impact of legume biomass and management on maize yield were simulated using APSIM version 7.7 (Holzworth et al. 2014). The use of APSIM to simulate maize production (Gaydon et al. 2017) and the performance of forage legumes in cereal crop systems (Carberry et al. 1996; Carberry et al. 1994; Robertson et al. 2005) have previously been validated for smallholder farming systems. For Eastern Indonesia, open pollinated and hybrid maize varieties commonly grown in West Timor have been validated for local conditions (Hosang 2014). While the forage legume model has not been validated for Eastern Indonesia, it has been validated in northern Australia (Carberry et al. 1996) under similar environmental conditions to those experienced in West Timor.

Simulations used daily solar radiation, temperature and precipitation from government meteorological stations for Naibonat (123°50'40"E, 10°05'49"S; 18m ASL) and Oenali (124°19'15"E, 9°52'51"S; 790m ASL) from 2001 to 2010. Annual rainfall averaged 1,308 mm at Naibonat and 1,465 mm at Oenali; Oenali had a longer wet season (Figure 4.1). Average solar radiation ranged from 17-23 mJ/m^2 at both sites. As there was no other suitable long term data available, climate data was allocated based on elevation with the Naibonat climate data was used for Uel, Manulai, Camplong and Ekateta locations and the Oenali data for Kesetenana and Oenai locations. Thus, one climate record was used for the lowland and midland sites and a different climate record was used for highland sites.

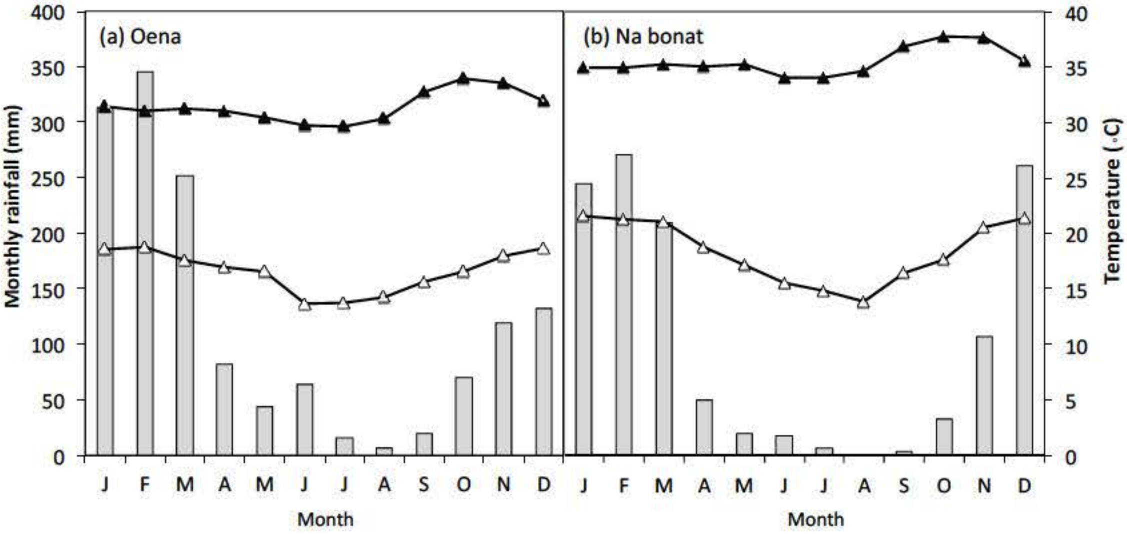

Figure 4.1. Average monthly rainfall (mm; bars) and mean minimum (hollow triangles) and maximum (solid triangles) temperature (˚C) used for APSIM simulations from Oenali (a) and Naibonat (b) meteorological stations.

Plant available water capacity (PAWC) for maize and butterfly pea were characterized based on soils in West Timor from the APSoil database: Vertic Inceptisol (Naibonat No675), Alfisol (Sillu No677), Alfisol (Oebola No754) and Grey Vertosol (Biloto

No678) (Dalgliesh et al. 2012). These PAWC were then combined with the measured soil total organic carbon and pH (Table 4.2) to parameterize the soils used for APSIM simulations.

A large unknown for soils in West Timor is whether there are any chemical constraints to forage and crop production and the level of soil organic carbon (SOC). Thus, soil chemistry was analysed for each case study farm. At each farm, the soil was collected from the main field allocated to crop production in February 2015. A minimum of three soil samples were collected along a diagonal transect using a 38 mm manually driven soil corer to a depth of 90 cm. The core was separated into layers 0-15, 15-30, 30-60 and 60-90 cm, air-dried for ≥4 days and then ground to ≤2 mm. These samples were sent to an Australian laboratory for analysis prior to which, to meet import standards, they were irradiated at Steritech Pty Ltd. Soil pH and electrical conductivity were measured using a 1:5 soil to solution ratio with deionized water and shaken for 1 hour. Total organic carbon was determined using a LECO TruSpec CN analyser. Labile phosphorus (P) was determine using the bicarbonate method of Colwell (1963) and sulfur (S) using the KCl40 method of Blair et al. (1991). Results indicate that, based on a critical P level of 21 mg/kg for butterfly pea (Haling et al. 2013), P was limiting at four of the six sites (Table 4.2). While P was limiting at four farms, it was not included in simulations as the APSIM model has not been developed for P limitations for forage legumes (Delve et al. 2009). Extractable S (critical level 6.5 µg/g for temperate pastures, Blair et al. 1991), EC and pH were non-limiting. Soil organic carbon % (SOC) was highly variable, ranging from 0.28 % (0-15 cm) at Oenai to 2.83 % (0-15 cm) at Ekateta.

Table 4.2. Soil type and measured soil chemistry (0-90 cm) for six farms in West Timor, Indonesia.

Farm (Soil)	Depth (cm)	pH_W	EC_W (uS/cm)	Organic C (%)	Colwell-P (mg/kg)	S (mg/kg)
Uel	0-15	8.2	174	1.31	13	11
(Inceptisol[A])	15-30	8.3	158	0.66	8	10
	30-60	8.4	159	0.50	5	9
	60-90	8.7	164	0.00	4	9
Manuali	0-15	7.2	157	2.17	32	14
(Vertosol[B])	15-30	7.2	119	1.11	19	12
	30-60	7.3	139	0.79	14	10
	60-90	7.8	226	0.58	11	9
Ekateta	0-15	7.7	228	2.83	17	16
(Shallow	15-30	8.0	172	1.36	5	9
Alfisol[C])	30-60	8.3	149	0.66	3	7
	60-90	8.6	129	0.31	2	5
Camplong	0-15	7.2	138	1.55	30	12
(Alfisol[D])	15-30	6.6	112	1.22	22	15
	30-60	6.5	91	0.62	21	23
	60-90	6.4	55	0.92	22	19
Oenai	0-15	8.0	142	0.28	7	7
(Alfisol[D])	15-30	8.3	131	0.06	4	4
	30-60	8.5	115	0.00	3	4
	60-90	8.5	106	0.00	3	3
Kesetnana	0-15	6.9	95	2.09	6	12
(Vertosol[B])	15-30	7.0	106	1.48	4	12
	30-60	7.5	145	0.87	2	10
	60-90	7.8	194	1.16	2	9

[A] Derived from APSoil database soil Vertic Inceptosol (Naibonat No675)

[B] Derived from APSoil database soil Grey Vertosol (Biloto No678)

[C] Derived from APSoil database soil Alfisol (Sillu No 677)

[D] Derived from APSoil database soil Alfisol (Oebola No754)

4.3.4. Simulated crop and forage production

Crop and forage simulations addressed three key factors: (1) the impact of legume management on legume biomass production, (2) maize yield responses to legume N for a range of biomass inputs and maize planting densities and (3) the interaction between N inputs, weed control and maize yield response. Baseline maize grain and stover yield were simulated for each farm from 2001 to 2010. As local landrace varieties dominate maize production in West Timor, local cultivar "timor oebola", was selected for its representative growing season length and grain yields (Hosang 2014). Maize was sown after 1 December following 15 mm of rainfall. Baseline simulations were designed to reflect local agronomic practices; maize was sown at 4 plants/m^2 and intercrops of cowpeas, cv. red caloona, were planted at 1 plant/m^2. To allow comparison between the case studies, these production parameters were used for all six farms. To ensure the same starting conditions each year, on 30 September each year soil water was reset to crop lower limit, and soil N and surface organic matter were reset to zero. This reset ensured that there was no carry over effects of previous management from year to year so that the changes due to the management options tested were not confounded over time.

Understanding the effects of legume management on biomass production is critical, with the three key options tested here including a maize-forage legume relay (forage legumes are planted inter-row at maize anthesis), annual rotations of forage legumes-maize (maize is planted after a one year stand of forage legumes) or permanent stands (forage legumes grown for five years without being terminated) (Dalgliesh et al. 2010, Figure 5.1). Forage legume rotation and relay simulations using APSIM's model of butterfly pea cv. Timor were used to determine the range of potential on-farm biomass production. Potential legume biomass production in a relay system was simulated where it was planted inter-row at maize anthesis (15 February) at 20 plants/m^2. Maize was managed as described above but cowpea intercrops were not included in the simulation. After maize harvest, butterfly pea biomass was cut and removed at 25 mm above ground level on the 3 April, 3 June and 3 August (the aggregate of these 3 cuts was used as the estimate of potential biomass production) and legumes were terminated on the 4 August. To simulate potential legume biomass in the rotation system legumes were planted at 15 plants/m^2 on 1 February and then cut and terminated on the same dates as the relay cropped butterfly pea, this was repeated on an annual basis. A permanent stand was simulated to benchmark potential legume production against the relay and rotation systems. This was simulated for butterfly pea planted at 15 plants/m^2 on 1 February and cut and removed on the same dates as the relay each year. As simulations didn’t account for declining plant population over time, annual dry matter production was multiplied by 0.8 in years 4 and 5, after which a new permanent stand was established. All biomass production estimates were the sum of the three biomass cuts.

The range of likely maize yield responses was simulated using a range of legume biomass inputs (1-6 t/ha) in combination with sole stands of maize at three different densities; 2, 4 and 6 maize plants/m^2. Scenarios simulated involved 1, 2, 3, 4, 5 and 6 t of legume shoot DM produced per ha, with both shoot and root biomass retained or shoot biomass removed and leaving only the corresponding root biomass. The corresponding root biomass was calculated using a root factor of 1.8 (45% below ground N), which is based on the mean value determined for a range of perennial pasture legumes (Peoples et al. 2012). At the start of each season (30 September), surface and soil organic matter was set for the various scenarios of butterfly pea shoot biomass using shoot C:N ratio of 11 (Odhiambo et al. 2010; Peoples and Herridge 1990) and root biomass C:N ratio of 25. These assumptions were based on root C:N reported for tropical legumes, which ranges from 7-32 (Gijsman et al. 1997; Peoples and Herridge 1990), as there is no data on the root C:N of butterfly pea. Also on 30 September each year, soil water was reset to crop lower limit, and soil N set to 0. Equal management was used across case study farms, with maize was planted after 1 December following 15 mm of rainfall; cowpea intercrops were not included in the simulations. Nitrogen-use efficiency of the maize crop (NUE; expressed as yield per kg legume N available) when both shoot and root biomass was retained was calculated using baseline values for maize N uptake and harvest soil N for the corresponding plant population when no legume shoot or root biomass was applied:

NUE = [maize yield (kg/ha)] / [[maize N uptake post legumes (kg/ha) – maize N uptake with no legume biomass applied (kg/ha)] + [soil N at maize harvest post legumes (kg/ha) – soil N at maize harvest with no legume biomass applied (kg/ha)]] [1]

Weed density effects on maize yield responses to additional N inputs were also simulated using the APSIM weed module. Simulations used a grassy C4 weed designed to represent johnson grass, with the parameters largely based on the APSIM sorghum module, which is based on the extensively validated APSIM-plant (Holzworth et al 2014). The impact of weed density (0, 1, 2, 3, 5, 10 and 20 plants/m^2) was assessed for a sole stand of maize sown after 1 December following 15 mm of rainfall at 2, 4 and 6 plants/m^2. The grassy C4 weeds germinated on 1 December and were controlled by cutting at 10 cm above ground level on 30 January and then terminating on 29

September each year. As soil N was reset on 30 September, only the impact of in-crop weeds, not fallow weeds, was assessed for these simulations. The interaction between weed management and N supply on maize yield was examined by comparing unfertilised maize with a synthetic fertiliser program that reflected moderate levels of N inputs (50 kg urea-N/ha applied at maize planting and 50 kg urea-N/ha applied 40 days after sowing (DAS)).

4.4. Results

4.4.1. Baseline simulated crop and forage legume production

There was large variation in simulated baseline maize yields with variation driven by differences in both climate (Figure 4.1) and soil conditions (Tables 4.1 and 4.2). The lowest baseline yields were at Oenai (0.9 t/ha), which had the lowest levels of SOC (0.3%, 0-15 cm). In comparison, all other sites had >1.5% SOC and had mean yields ≥2.5 t/ha. Importantly, yield variability was higher for midland farms (range 0.2-4.5 t/ha) and highland farm Kesetnana (range 0.5-4.2 t/ha) than for Oenai (range 0.2-1.5 t/ha) and lowland farms (range 1.4-4.4 t/ha). On farm yields reported by participating farmers were commonly 60% of the simulated yields (Figure 4.2).

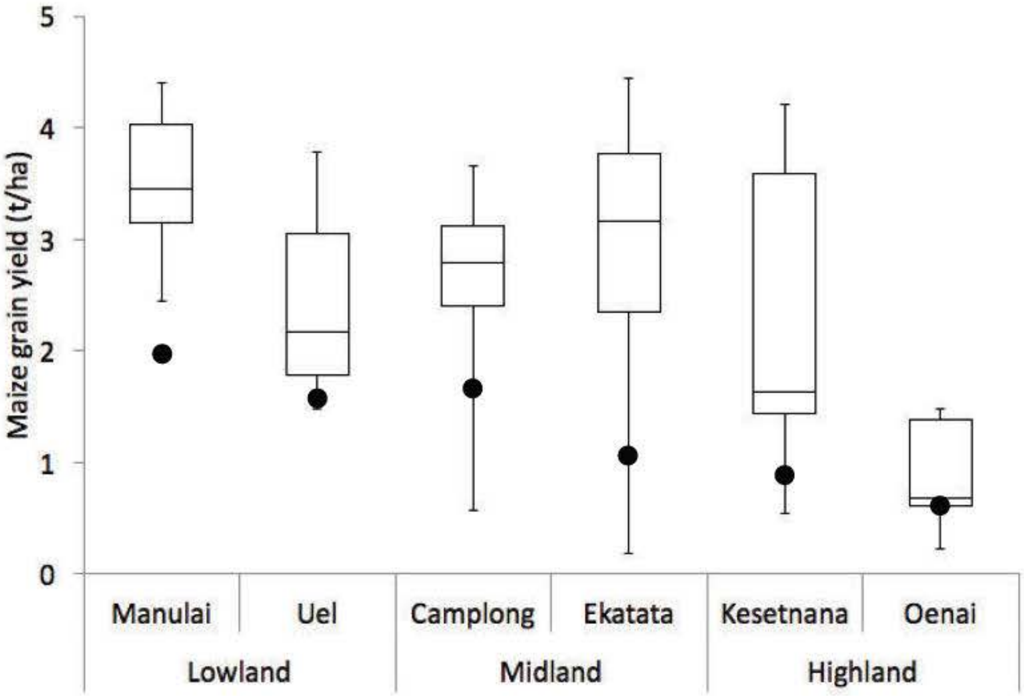

Figure 4.2. Baseline maize grain yield for six farms in West Timor, Indonesia. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations. Circles represent average on-farm yields as determined by participating farmers (N≥10 at each village).

Forage legume simulations for the relay, rotation and permanent stand showed legume shoot biomass ranged from 1-13 t/ha. Importantly, the upper potential for forage legume production differed with management and agro-climatic conditions. Butterfly pea commonly produced twice as much shoot biomass when grown as a rotation or permanent stand than when grown as a relay (Figure 4.3). Across the different agro-climatic conditions, biomass production was commonly 1-2 t/ha higher for highland farms than for lowland or midland farms, due to the higher rainfall and longer wet season at these sites (Figure 4.1). As biomass production drives N fixation and inputs (Peoples et al. 2012), this indicates that there is a broad range of N inputs that could be achieved depending on environmental conditions and legume management. As with the simulate maize yields, it is likely that on-farm biomass production is likely to be only 60% of simulated yields. Thus, the shoot biomass production of forage legumes on-farm is expected to range from 1-6 t DM/ha (Nulik et al 2013). The associated N inputs and implications for subsequent maize crops across this range of legume production is explored below.

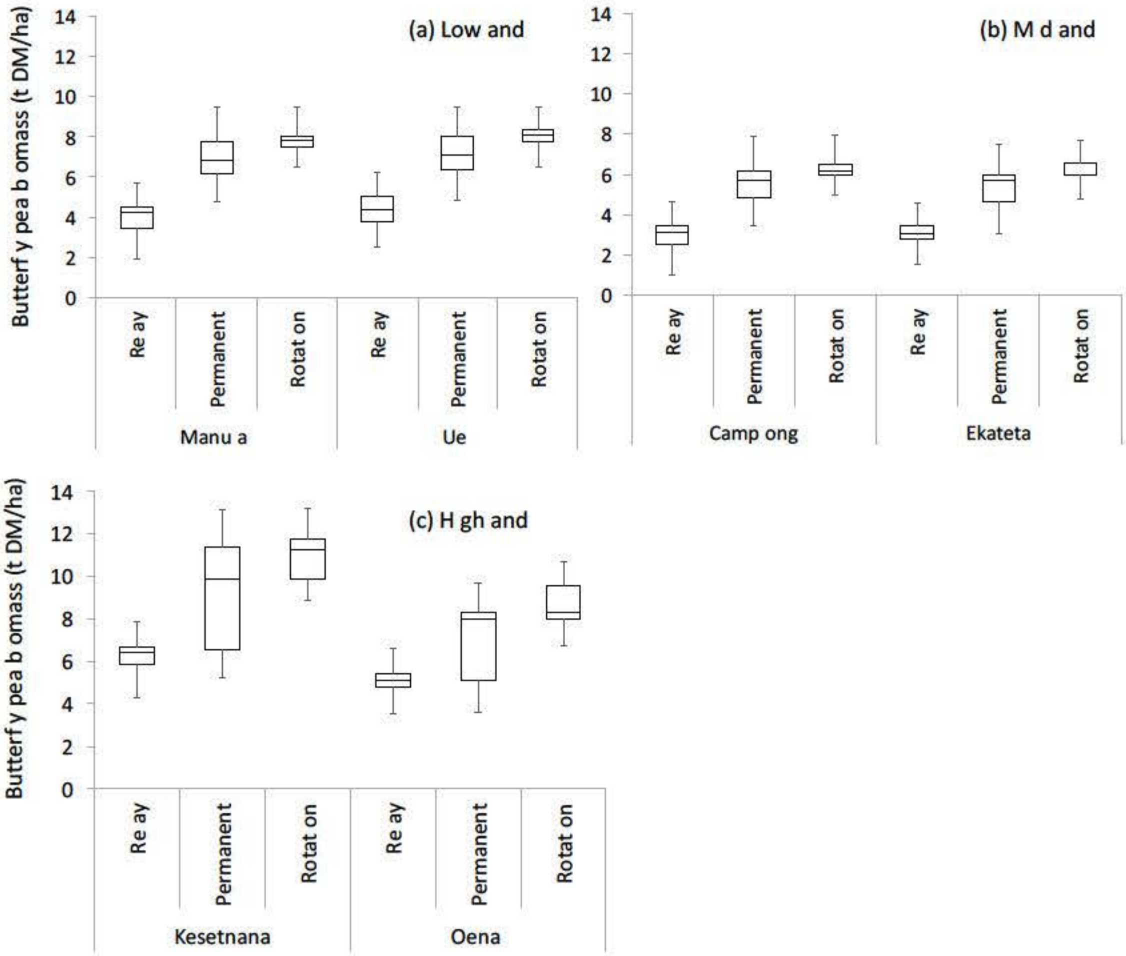

Figure 4.3. Butterfly pea annual shoot biomass production for (a) lowland, (b) midland and (c) highland farms in West Timor, Indonesia, when butterfly pea is managed as a maize-butterfly pea relay, permanent stand or maize-butterfly pea rotation. Biomass is the aggregate of cuts in April, June and August. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations.

4.4.2. Maize yield responses to legume biomass

The effect of retaining the whole legume plant on subsequent maize yield was larger for higher maize plant densities (and farms with lower SOC and higher rainfall). There was little or no response to legume biomass when maize was planted at 2 plants/m^2 at five of the six locations, the exception was when SOC was very low (0.3% 0-15 cm; Oenai) (Figure 4.4 and 4.5). The response to legume production increased with increasing plant population, with a larger response evident for 6 plants/m^2 than 4 plants/m^2 for all farms. To illustrate, at Kesetnana, where SOC was moderate (2.1% 0-15 cm) and rainfall was low (1,308 mm/year), moderate legume production (3 t/ha shoot biomass) increased median yield by 0.9 t/ha for 4 plants/m^2 compared to 1.8 t/ha for 6 plants/m^2. However, the magnitude of the response for 4 and 6 plants/m^2 varied between sites, with larger yield responses to increasing legume inputs for higher rainfall environments (Oenai and Kesetnana) and when SOC was low (Oenai and Uel) (Figure 4.4 and Figure 4.5). For example, moderate legume production (3t shoot DM/ha) increased median maize yield by 1.8-3.0 t/ha at these responsive sites (Oenai, Kesetnana and Uel) compared to only 0.9-1.3 t/ha for less responsive sites (Camplong, Ekateta and Manulai), which had higher SOC or lower rainfall. Notably, for all sites, retaining the whole legume plant did not increase yield in the less productive years, rather it increased average and maximum yield. Importantly, at five of the six sites, maize yields plateaued at high levels of legume inputs indicating this had exceeded the N demand of the crop. Therefore, when all legume biomass was retained at responsive sites (Kesetnana and Uel) there was no additional yield benefit above legume production of 4 t DM/ha, while at less responsive sites (Camplong, Manulai and Ekateta) there was no additional yield benefit above legume production of 2-3 t DM/ha.

The exception was where SOC was very low (Oenai) as maize yields did not plateau at high levels of legume production (6 t shoot DM/ha).

While retaining both shoot and root biomass could increase maize yield, harvesting shoot biomass and retaining only root biomass commonly resulted in either no change or a decrease in maize yield. At sites with higher rainfall (Oenai and Kesetnana) removing shoot biomass decreased median maize yield regardless of maize density (Figure 4.4 and 4.5). The most dramatic impact was when there was high rainfall and low SOC (Oenai), as removing more than 4 t shoot biomass/ha reduced median maize grain yield to 0 t/ha at 6 plants/m^2. This meant that grain was only harvested in 50% of years rather than every year. Despite these results, root biomass did increase maximum grain yield indicating that the impact of legume root N inputs was highly seasonal. A similar trend was evident for midland (Camplong and Ekateta) and lowland (Uel and Manulai) farms with harvested legumes increasing maximum grain yield in some years, although there was little change in median or average grain yield in response to increasing quantities of root biomass.

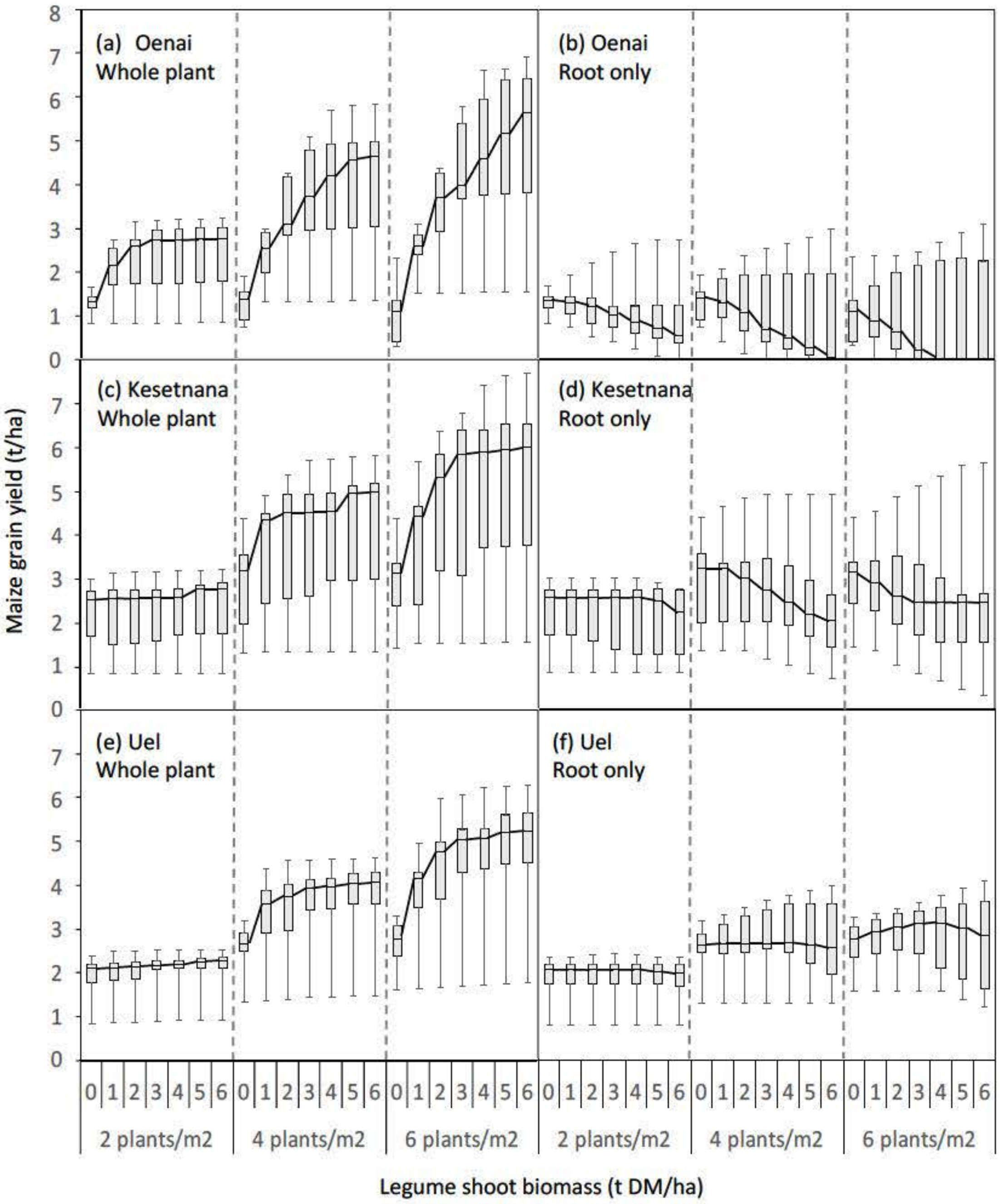

Figure 4.4. Maize grain yield response to increasing amounts of legume shoot biomass when all plant biomass is retained including roots ("whole plant") or when shoot biomass is removed and only root biomass is retained ("root only") for three different plant populations of maize (2, 4 and 6 plants/m^2) at Oenai, Kesetnana and Uel villages in West Timor, Indonesia, which were sites with high yield responses to legume N. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations, the trend line represents median value.

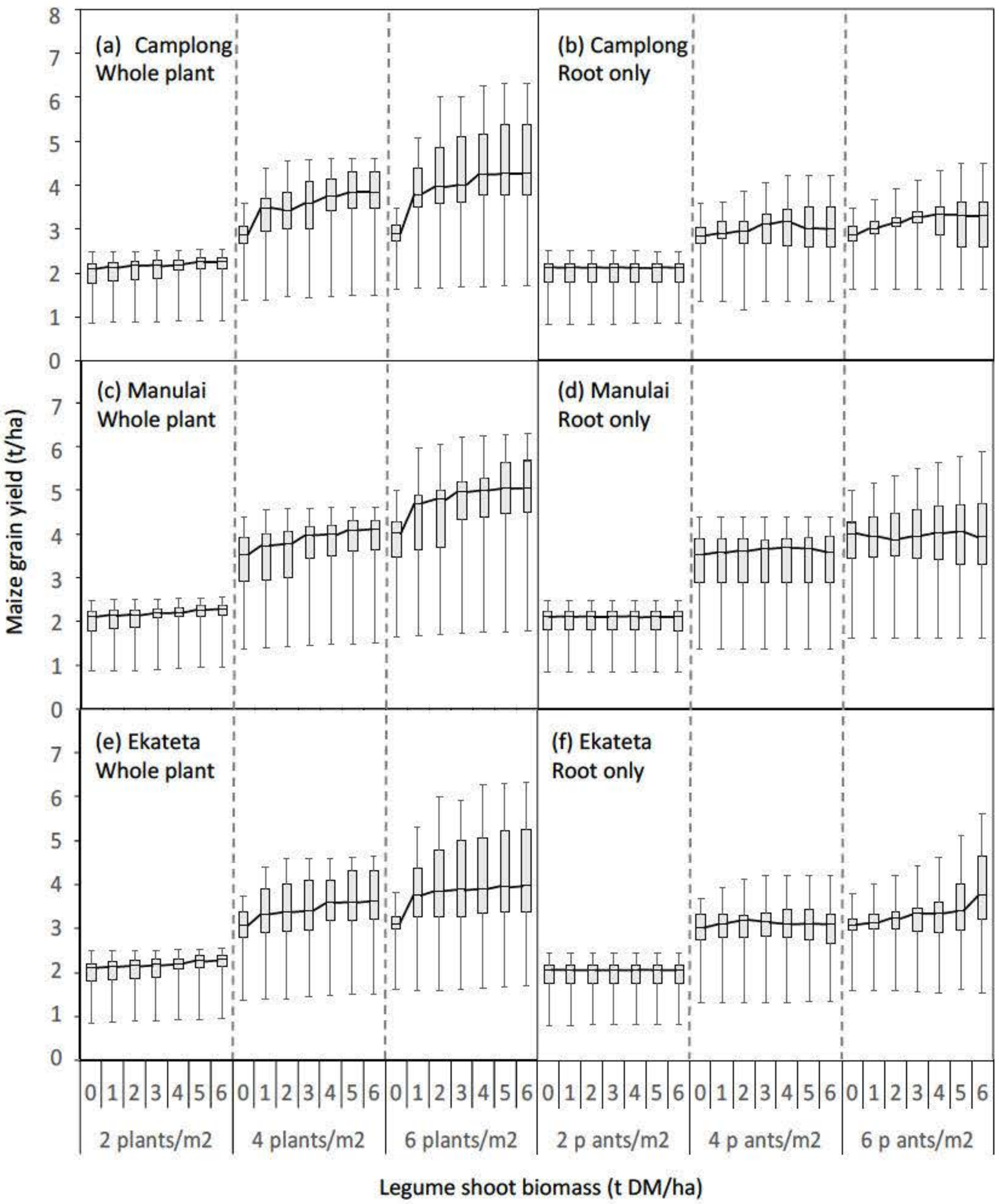

Figure 4.5. Maize grain yield response to increasing amounts of legume shoot biomass when all plant biomass is retained including roots ("whole plant") or when shoot biomass is removed and only root biomass is retained ("root only") for three different plant populations of maize (2, 4 and 6 plants/m^2) at Camplong, Manulai and Ekateta villages in West Timor, Indonesia, which were sites with lower yield responses to legume N. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations, the trend line represents median value.

4.4.3. Maize N uptake and nitrogen use efficiency

N uptake in baseline scenarios (no legume biomass) indicated there was large variability in the soils ability to supply N to the maize crop (Figures 4.6 and 4.7). At high maize populations, baseline N uptake commonly declined with decreasing SOC, with higher median baseline N uptake (43-78 kg N/ha) at sites with higher SOC (1.6-2.8%, 0-15 cm) than when SOC was <0.5% (24-25 kg N/ha). In addition, increasing plant population increased baseline N uptake for all sites except that with low SOC (Oenai). This was because maize yields at Oenai, and consequently N uptake, didn't increase in response to increasing maize density.

Maize N uptake reflected the changes in maize yield in response to increasing amounts of legume biomass inputs (Figures 4.6 and 4.7). When whole plant biomass was retained, little or no additional N was accumulated by maize at 2 plants/m^2; the exception was at Oenai with low SOC. In comparison, there were large increases in N uptake due to legume inputs at maize densities of 4 and 6 plants/m^2. Moderate legume production (3 t shoot DM/ha) increased maize N uptake by 13-40 kg N/ha at 4 plants/m^2 and by 33-50 kg N/ha at 6 plants/m^2. This increase in N uptake was in response to increased N supply which was driven by both pre-crop N mineralisation as well as in-crop mineralisation. However, maximum N uptake approached 120 kg N/ha under high legume inputs, which appeared to be close to the maximum average N uptake achievable under these management and agro-climatic conditions. As soil N and plant available water were the key agronomic factors determining simulated yields, this indicates that when N uptake plateaued, maize yields were then water limited rather than N limited.

When legume shoot biomass was removed and only root inputs were considered, maize N uptake decreased by 1-6 kg N/ha where maize yield decreased (Oenai and Kesetnana) but increased by up to 14 kg N/ha when maize yield remained unchanged or increased slightly (<0.7 t/ha; Camplong, Manulai, Ekateta and Uel). Reflecting yield responses, there was little or no change in N uptake at 2 plants/m^2. However, at maize densities of 4 and 6 plants/m^2 with the increase in N demand of these crops, N uptake increased in response to greater legume inputs even when there was no corresponding yield response.

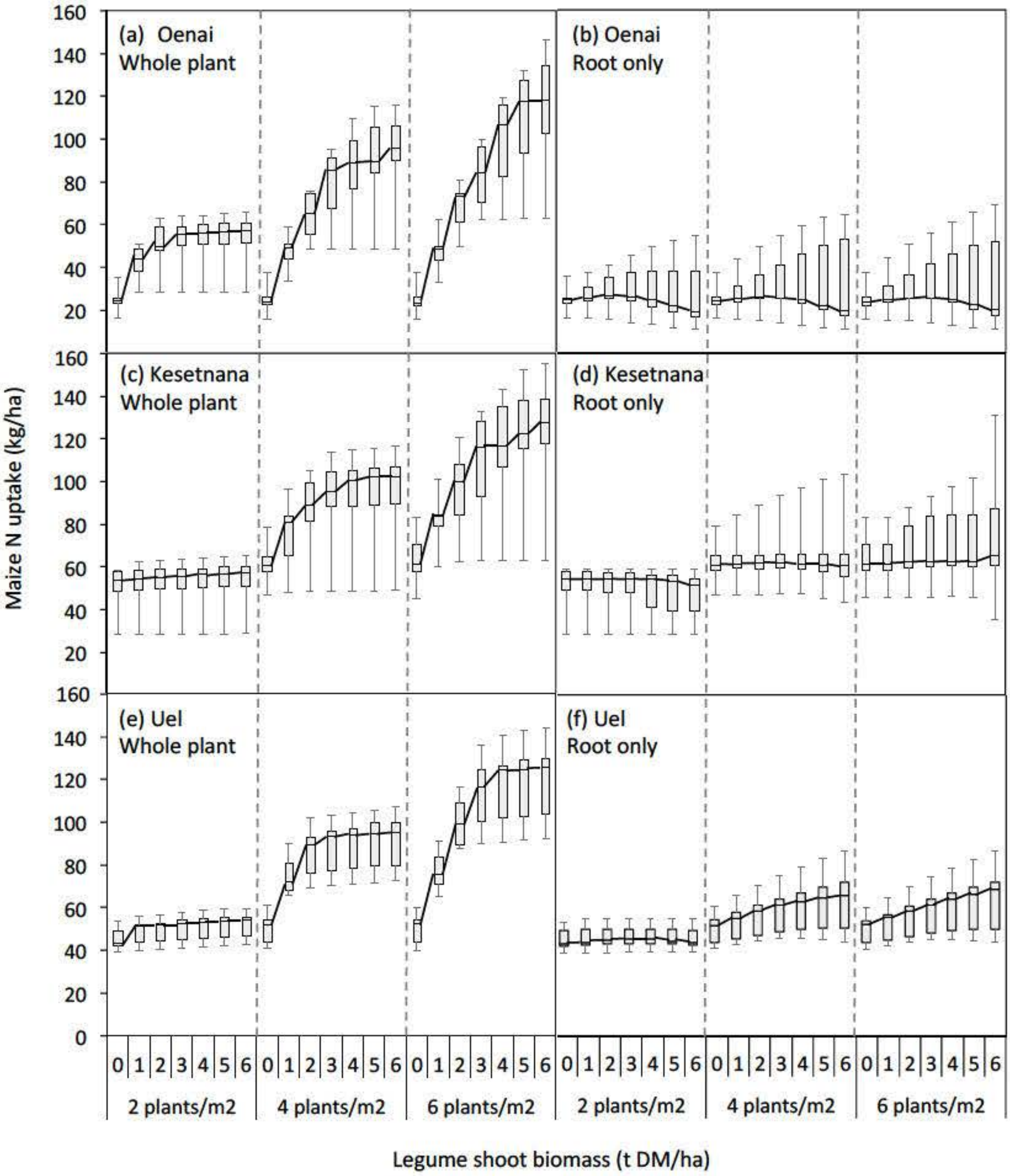

Figure 4.6. Maize N uptake response to increasing amounts of legume shoot biomass when all plant biomass is retained including roots ("whole plant") or when shoot biomass is removed and only root biomass is retained ("root only") for three different plant populations of maize (2, 4 and 6 plants/m^2) at Oenai, Kesetnana and Uel villages in West Timor, Indonesia, which were sites with high yield responses to legume N. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations, the trend line represents median value.

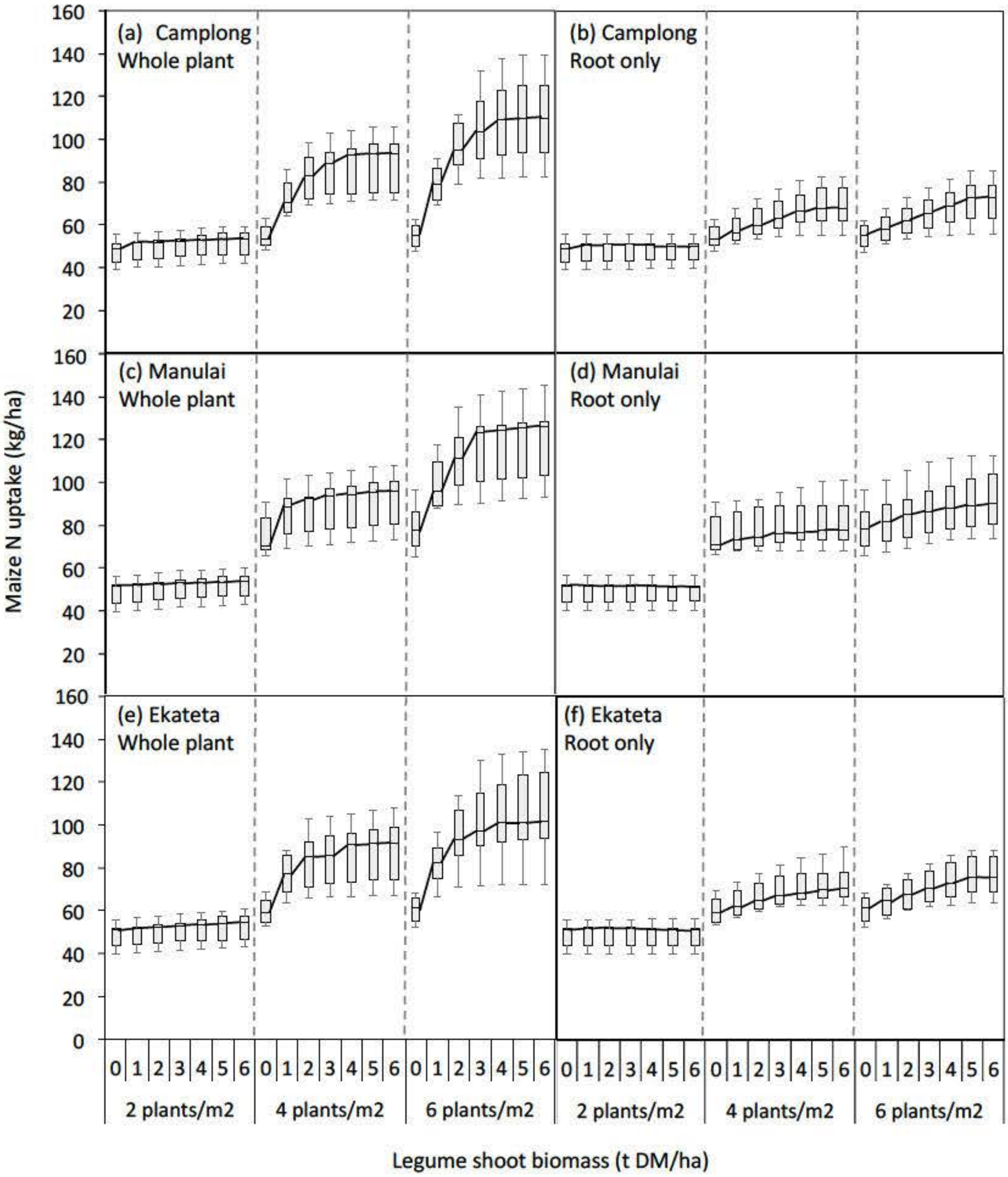

Figure 4.7. Maize N uptake response to increasing amounts of legume shoot biomass when all plant biomass is retained including roots ("whole plant") or when shoot biomass is removed and only root biomass is retained ("root only") for three different plant populations of maize (2, 4 and 6 plants/m^2) at Camplong, Manulai and Ekateta villages in West Timor, Indonesia, which were sites with lower yield responses to legume N. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations, the trend line represents median value.

Nitrogen use efficiency (NUE; expressed as yield per kg legume N available) was similar across all sites (Figure 4.8). This demonstrates that when variability in the soils capacity to provide N was excluded, the yield response to legume N was similar across the agro-climatic conditions that were simulated. Results indicated that there was little additional yield benefit achieved when >50-75 kg N/ha of additional N was available to the maize crop. This reflects the plateauing of maize yields at high levels of legume inputs shown in Figure 4.3 and Figure 4.4. In addition, NUE was higher with increasing maize density and this increased more as maize density increased from 2 to 4 plants/m^2 than from 4 to 6 plants/m^2.

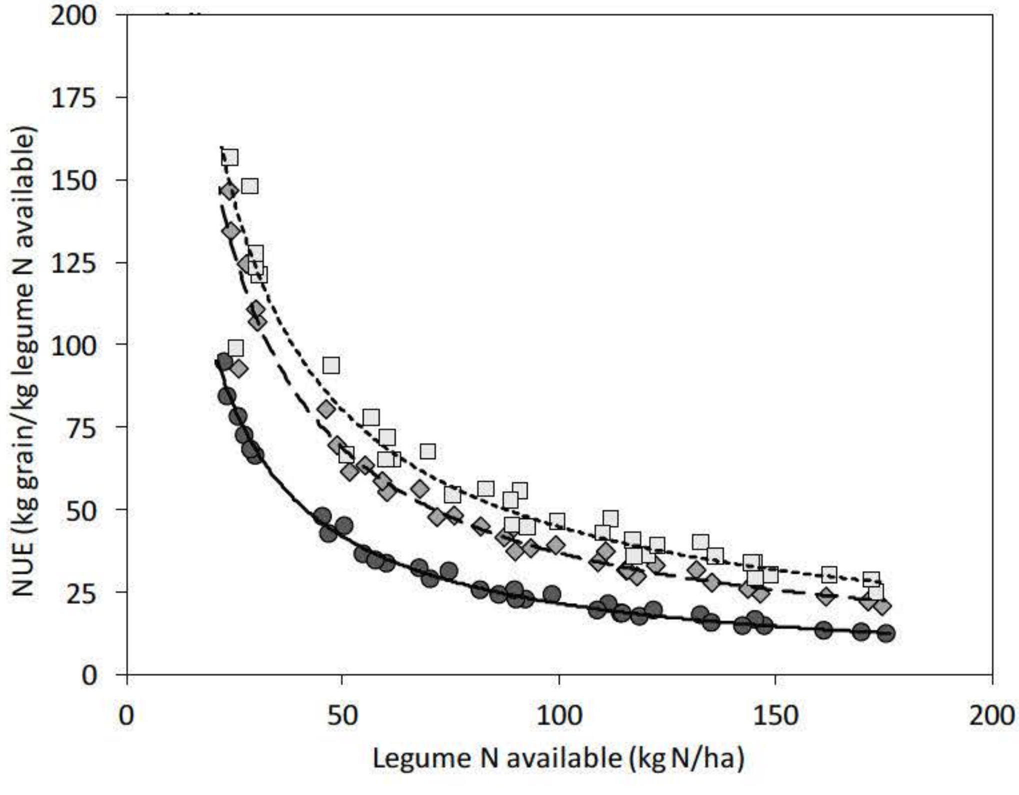

Figure 4.8. Nitrogen use efficiency (NUE; kg yield per kg of legume N available) for maize at 2 plants/m2 (circle; $y=1743x^{-0.95}$, $R^2=0.99$), 4 plants/m^2 (diamond; $y=2271x^{-0.90}$, $R^2=0.98$) and 6 plants/m^2 (square; $y=2152x^{-0.84}$, $R^2=0.96$) across 6 sites in West Timor, Indonesia. Each point is average NUE for 10 years of simulations.

4.4.4. Soil mineral N pre and post maize crop

At maize planting, baseline soil N ranged from 13 kg N/ha at Oenai to 35 kg N/ha at Manulai. Soil N at maize planting increased linearly in response to increasing legume shoot biomass inputs, with an additional 14-18 kg N/ha for each tonne of shoot biomass retained (data not shown). While this N mineralisation was higher than expected (Chapter 2), rapid mineralisation is likely to occur because of the low C:N ratio (11) of legume shoot biomass, high temperatures and pre-crop rainfall (Figure 4.1). In comparison, when only root biomass (C:N 25) was retained there was no change in soil N at maize planting.

Soil N post-harvest was also quantified so we could understand any additional benefits for N available for subsequent crops, the residual N that was susceptible to leaching and NUE of the legume N available to the crop (Figure 4.8). At maize harvest, the amount of residual soil N increased with increasing legume production. Consequently, at 2 plants/m^2, soil N at maize harvest increased linearly with increasing legume shoot biomass because there was little increase in maize N uptake due to the low N demand at low maize densities (Figure 4.9 and Figure 4.10). Thus, at 2 plants/m^2 there was an additional 20-29 kg N/ha left at maize harvest for each additional tonne of legume shoot biomass retained. At higher maize densities (4 and 6 plants/m^2) there was a similar increase in soil N at maize harvest once crop N needs had been met. Notably, there was little or no increase in soil N post maize harvest when shoot biomass was removed, with an increase in soil N of only 7 kg N/ha after the highest legume production scenarios.

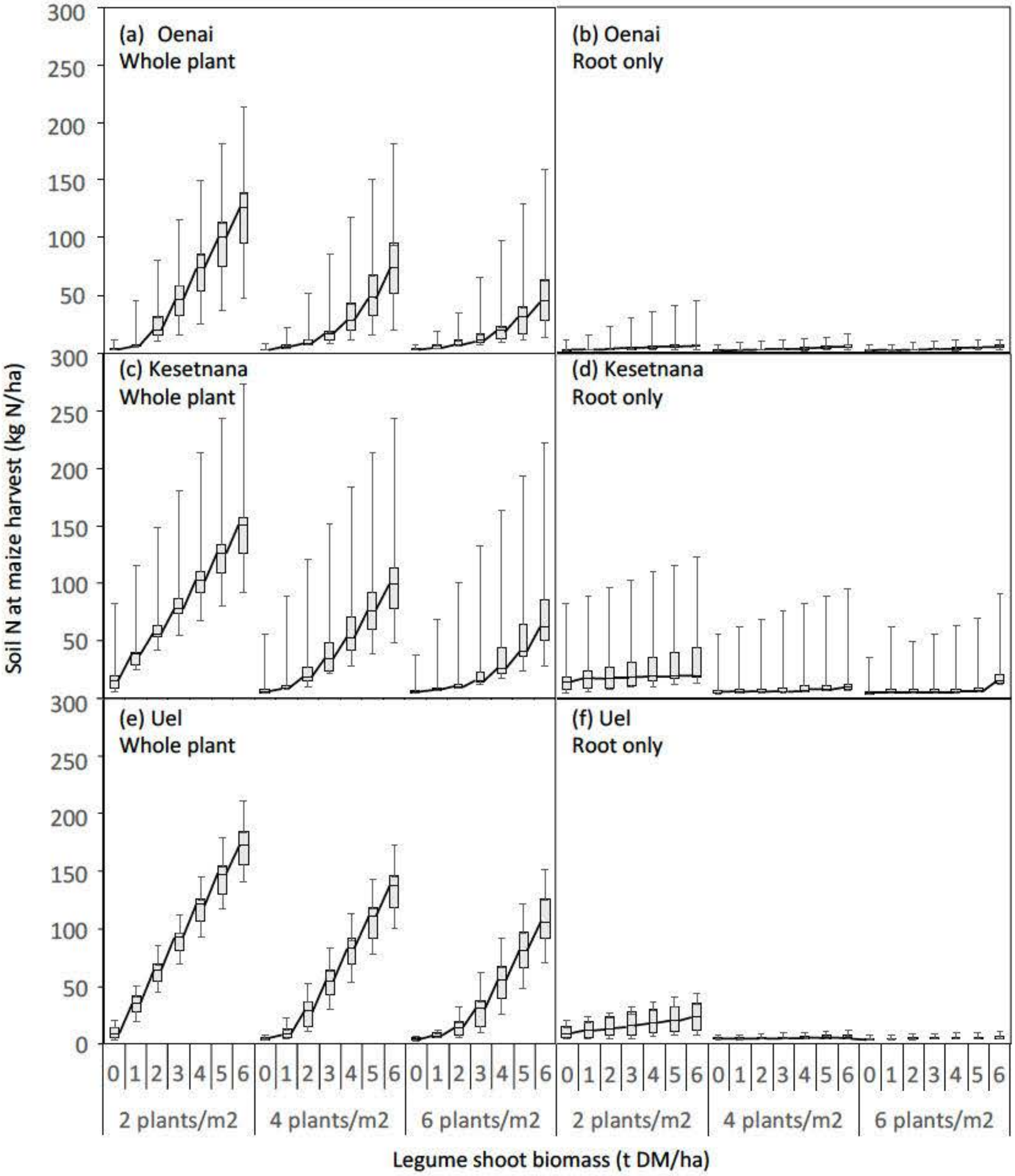

Figure 4.9. Soil N at maize harvest (0-180 cm) in response to increasing amounts of legume shoot biomass when all plant biomass is retained including roots ("whole plant") or when shoot biomass is removed and only root biomass is retained ("root only") for three different plant populations of maize (2, 4 and 6 plants/m^2) at Oenai, Kesetnana and Uel villages in West Timor, Indonesia, which were sites with high yield responses to legume N. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations, the trend line represents median value.

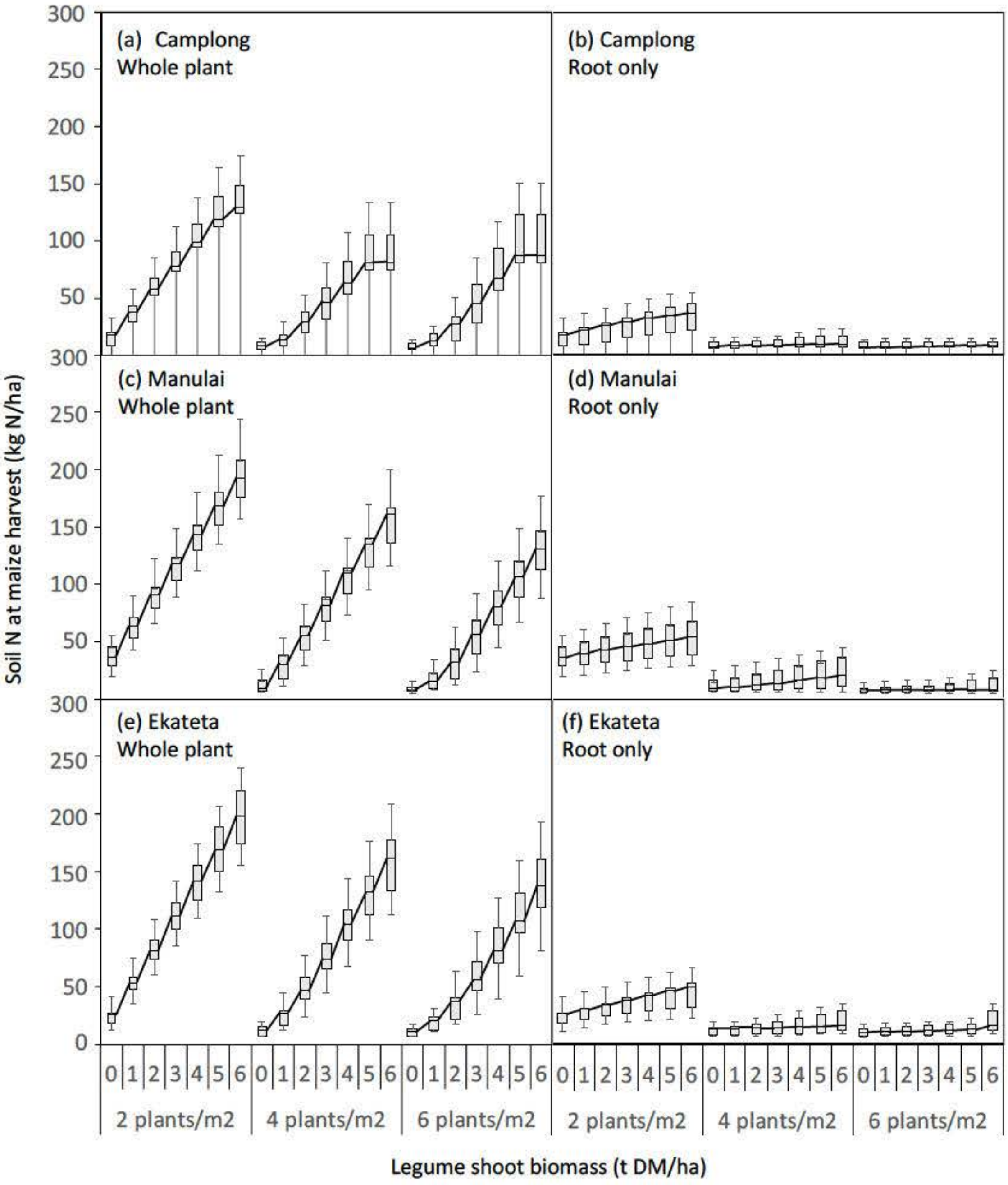

Figure 4.10. Soil N at maize harvest (0-180 cm) in response to increasing amounts of legume shoot biomass when all plant biomass is retained including roots ("whole plant") or when shoot biomass is removed and only root biomass is retained ("root only") for three different plant populations of maize (2, 4 and 6 plants/m^2) at Camplong, Manulai and Ekateta villages in West Timor, Indonesia, which were sites with lower yield responses to legume N. The boxes represent the lower and upper quartiles and median yields, whiskers represent maximum and minimum yields for 10 years of simulations, the trend line represents median value.

4.4.5. Weed management effects

Weed management is an issue in current maize systems in West Timor, hence the impacts of weed competition on maize grain yield responses to enhanced N supply was also explored. Once the weed populations reached >3-5 plants/m^2 an additional 100 kg N/ha failed to increase maize yield at all sites and maize plant densities (see the example Figure 4.11). Thus, if weed populations are not maintained below 5 plants/m^2, there is no yield benefit from additional N inputs. Importantly, simulations also indicated that weed competition had a larger impact on competition for N than soil water. To illustrate, when there were no weeds, fertilised (2.8 t/ha) and unfertilised maize yields (2.5 t/ha) at Uel were similar. However, when weed density increased from 0 to 1 weed/m^2, fertilised maize yield decreased by 0.3 t/ha, while unfertilised maize yield decreased by 1.2 t/ha (Figure 4.11). This demonstrates that weeds had a larger impact on maize yield when N availability was limited. Importantly, fertilised maize yield with 1 weed/m^2 was similar to unfertilised maize yield with no weeds, indicating that maize yield can be equally reduced by low populations of weeds (1 plant/m^2) as it is by N limitations. Hence, adequate weed control is required to realise the yield benefits from legume N.

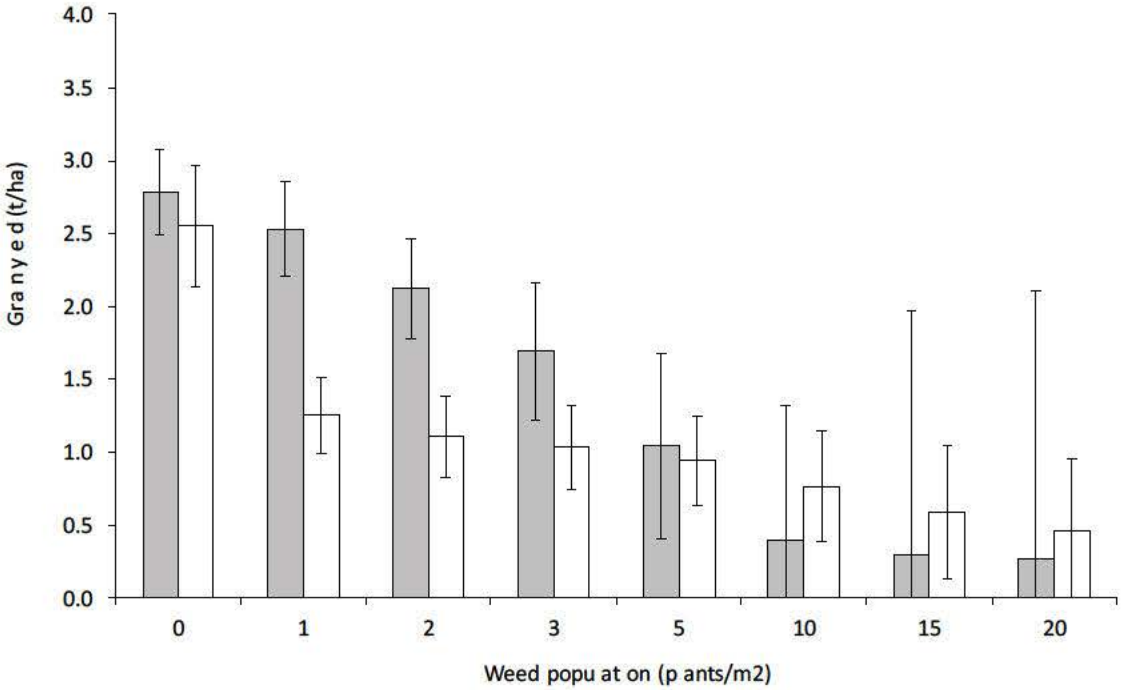

Figure 4.11. Impact of weed population on maize grain yield with an additional 100 kg N/ha (grey) or no additional N (white) at Uel. Maize was planted at 2 plants/m^2. Average yields are shown ± standard error.

4.5. Discussion

Simulations indicated that yield responses to forage legumes in subsequent maize crops are impacted by legume management (retain vs. remove shoot biomass), maize plant population and agro-climatic conditions. This paper found that forage legumes can have a large potential benefit for subsequent maize yields and N uptake when all plant biomass is retained, but when shoot biomass is removed the impact is either small or neutral. However, this simulated yield response to legume N depended on maize plant density, with greater yield responses at 4 and 6 plants/m^2 and little or no response at low maize density (2 plants/m^2). Agro-climatic conditions also affected legume N benefits, with a larger yield response for sites and seasons with low SOC and higher rainfall. However, achieving these yield responses requires good agronomic practice, including weed control, during the maize crop.

4.5.1. Maize and forage legume management affect yield responses

Maize density was a critical factor driving simulated responses to legume inputs. At 2 plants/m^2 there was little or no yield response to legume inputs. This was because low plant populations have low demand for N and, thus, there was little response to additional N. In comparison, at increased maize densities, high legume inputs (6 t shoot DM/ha) increased average maize yield by 0.4-2.5 t/ha when planted at 4 plants/m^2 and by 1.0-3.5 t/ha for 6 plants/m^2. These higher yields responses were driven by the additional crop demand for N of 16-67 kg N/ha for 4 plants/m^2 and 40-88 kg N/ha for 6 plants/m^2. As low plant populations are common in smallholder farming systems (Hosang 2014; Tittonell et al. 2007), intensification of maize production may be required to ensure such yield responses are achieved. However, optimal sowing densities for set N inputs are likely to differ with agro-climatic conditions and farmers' risk management strategies. Research at two sites in Mozambique with similar rainfall (723 mm), indicated that optimal maize density when 30 kg N/ha was applied was 2.5 plants/m^2 at a site with 0.7% SOC (0-15 cm) compared to 4.5 plants/m^2 for a site with 1.2% SOC (0-15 cm) (Roxburgh and Rodriguez 2016). Thus, maize plant density must be tailored to the local agro-climatic conditions and N input levels to ensure maximum yield benefits are realised.

While large yield increases are achievable, high legume inputs (5-6 t shoot DM/ha) are not required to achieve these yield responses. For common plant densities (4 plants/m^2), average maize yield commonly plateaued when legume inputs were >2-3 t DM/ha, while for 6 plants/m^2 yields plateaued once legume production was >3-4 t DM/ha. N uptake reflected this, with average N uptake plateauing at 110-120 kg N/ha, with NUE estimates indicating there was little additional yield benefit when >50-75 kg N/ha of additional N was available to the crop (Figure 4.8). Consequently, there were high levels of residual soil N at maize harvest (32-159 kg N/ha) when legume inputs exceed this demand. This surplus N not used by the maize crop could be available for subsequent crops but is also prone to losses through leaching or denitrification (Peoples and Herridge 1990). This does indicate that legume N benefits may be achieved by cutting and removing biomass on only one occasion, and retaining the subsequent regrowth to increase soil N and crop yield. In addition to these management options, synchronising N release with crop N demands can also increase NUE and reduce N losses (Crews and Peoples 2005). While, this research only considered crop NUE, assessing the net inputs of N per unit of farm output may provide a more robust measurement in crop-livestock systems, as such measurements can account for the N-use efficiency of manure N and soil organic matter in feed production (Gerber et al. 2014). Such analysis could elucidate the efficiency trade-offs between allocating legume N to crop or livestock production, thus identifying forage legume management options with the highest whole farm NUE. Therefore, while forage legumes can provide large amounts of N to the subsequent crop, increasing NUE is critical to maximising production benefits and minimising negative environmental impacts.

How legume biomass is used will greatly impact its benefits to following cereal crops. While retaining a portion or all of the legume shoot biomass can contribute large amounts of N to the subsequent crop, smallholder farmers are likely to prefer to allocate biomass to livestock production rather than increasing soil fertility (Chapter 6, Dagliesh et al. 2010; Giller et al. 2009). We found that when all shoot biomass was removed for fodder there was either little impact or a reduction in maize yield and only small changes in maize N uptake (0-16 kg N/ha). Thus, removing legume shoot biomass instead of retaining it on the field reduced simulated maize N uptake by 16-72 kg N/ha. These results are consistent with experiments in West Timor and in southeast Queensland which have also found that, when shoot biomass is removed, there is either no or limited yield benefit to the subsequent crop (Chapter 3, Dalgliesh et al. 2010, Bell et al. 2017). Despite this, in northern Australia, verano (*Stylosanthes hamate*) used for hay contributed 21 kg N/ha to the following maize crop (Jones et al. 1996). Thus, soil N benefits are achievable when shoot biomass is removed for fodder however, these benefits are likely to be variable and unreliable. Grazing is an option which may provide more consistent soil N benefits as less N is removed from the system. For example, in temperate Australia total N removed and lost from pastures was 29-57 kg N/ha for grazed systems compared to up to 89 kg N/ha in hay (Peoples et al. 2012). However, farmers must have sufficient labour and technical skills to manage intensive grazing systems and be able to prevent others' livestock from grazing the legumes (Chapter 6).

4.5.2. Spatial and temporal variability of yield responses to legume N

Importantly, the yield response to legume production also differed between sites and years, with a larger yield response evident for sites and seasons with higher rainfall and lower SOC. To illustrate the impact of rainfall, Kesetnana and Manulai farms had similar SOC (2.1-2.2 %) but Kesetnana had a longer wet season and an extra 157 mm/year, as a result retaining moderate levels of whole plant biomass (3 t shoot DM/ha) increased average yield by 1.9 t/ha at Kesetnana compared to 0.9 t/ha at Manulai. Importantly, temporal variability in rainfall also influenced the impact on maize yield as, in poor seasons, crop yield was water limited rather than N limited and thus there was no response to additional N. These water limiting conditions can also constrain legume biomass production and N fixation (Armstrong et al. 1998; Bell et al. 2017; Giller 2001; Peoples et al. 2009). Consequently, there must be sufficient rainfall over two wet seasons, firstly, to enable sufficient inputs of legume N and then, secondly, to allow for adequate crop yield potential to utilise this legume N. Thus, options which maximise fallow and crop water use-efficiency will be essential to achieving more consistent yield benefits from forage legume production.

Given the role of soil organic matter as source of N for crops (Cookson et al. 2005), yield responses to legume N were larger when SOC was low, as the ability of the soil to supply N for the crop was lower. This was particularly evident at Oenai (0.3% SOC, 0-15 cm), with larger yield benefits from retaining legume biomass than for other locations. However, when shoot biomass was removed, there were large negative effects for sites with low SOC. This was particularly important at Oenai, where high levels of root biomass resulted harvest failure when maize was planted at higher densities. This decrease in simulated yield was driven by a decline in crop N uptake in poor years, which is likely to be driven by higher levels of N immobilisation in soils with low SOC. Although, a better understanding of legume below ground N and how it is affected by biomass removal (Unkovich et al. 2010) is required to further elucidate how legume management affects the N contribution to the subsequent crop. In addition to the variability that exists between sites (Dalgliesh et al. 2010), soil fertility gradients within smallholder farms are also likely to affect the response to additional N inputs (Tittonell et al. 2013). Therefore, spatial variability in SOC at a farm and regional levels is likely to determine where the largest production benefits can be achieved from forage legume introduction.

4.5.3. The potential of forage legumes to close maize yield gaps

Simulations indicate that there are a large yield gaps between actual on-farm yield and water limited yield (Table 4.3). Moderate forage legume production (3 t shoot DM/ha) can help close this yield gap. However, the yield gap between actual farm yield and simulated attainable yield (without legumes) indicates that there are a range of other important agronomic improvements which can increase maize yield without additional N inputs. Weed control is critical as there is little yield benefit from additional N if weed density is ≥5 plants/m^2. To illustrate, there was little difference between actual farm maize yields and yields when an additional 100 kg N/ha was applied but weed control was poor (Table 4.3). Maize density is also important, as increasing density from 4 to 6 plants/m^2 increased water limited yield by 1.1-2.0 t/ha. Low levels of soil P (Table 4.2) may also affect maize yield responses. Roxburgh and Rodriguez (2016) suggest that improvements in basic agronomic management, such as weeding and planting time, should be introduced before costlier or, in the case of forage legumes, labour intensive (Chapter 6) technologies are introduced. Therefore, simulations indicated that forage legumes help can close the gap between actual farm yield and water limited yields but only if accompanied with good agronomic management.

Table 4.3. Yield gaps for maize production at six sites in West Timor, Indonesia, comparing maize produced using current management, water limited yield and weed limited yield.

Maize yield (t/ha)	Maize (plants/ m^2)	Low responsive sites			High responsive sites		
		Oenai	Kesetnana	Uel	Camplong	Manulai	Ekateta
Current management							
Actual farm yield	4	0.6	0.8	1.6	1.7	1.9	1.2
Attainable yield[A]	4	1.5	4.2	3.7	3.6	4.4	4.5
Water limited yield[B]							
Medium density	4	5.9	5.9	4.4	4.7	4.7	4.6
High density	6	7.0	7.4	6.4	6.3	6.2	6.0
Weed limited yield (5 weeds/m^2)[C]							
Medium density	4	1.5	1.4	1.6	1.7	1.4	1.6
High density	6	1.2	1.7	1.5	1.9	1.7	1.8

[A] Maximum on-farm yield potential limited by current management and rainfall (source Figure 4.2)

[B] Maximum yield achievable under rainfed conditions when soil N is non-limiting and maize is grown without intercrops or weeds (source Figure 4.4 and Figure 4.5)

[C] Maximum yield achievable under rainfed conditions when an additional 100 kg N/ha is applied but maize is grown with weeds at 5 plants/m^2 (source Section 4.4.5 and Figure 4.11)

The system by which forage legumes are integrated with maize will influence their potential biomass production and N inputs for the subsequent crop. Here we predicted higher legume biomass production when grown in a rotation (3.6-6.1 t/ha) than a relay (1.7-3.4 t/ha). Consequently, based on simulated average legume biomass production, average maize yield at 6 plants/m^2 will increase by 1.0-3.7 t/ha for a rotation compared to 0.6-3.0 t/ha for a relay. However, these options have implications for maize management and the proportion of arable land that is allocated to food crops or forages. For a relay, the area of maize is maintained and forage legumes replace other intercrops (e.g. cowpea), which are commonly intercropped with maize (Ngongo 2011). In comparison, rotations can be planted on uncultivated land but when land availability is limited forage legumes may have to replace food crops. Consequently, to be a viable option under land constrained conditions, a rotation must provide sufficient yield or economic benefits to replace the maize grain which has been replaced by forages (Chapter 5). Thus, effective forage legume and maize management is required to realise yield benefits from legume N, with farmers requiring sufficient resources, such as labour and land, and technical skills to maximise on-farm benefits (Chapter 6, Tittonell et al. 2009; Giller et al. 2011).

4.5.4. Uncertainties of the simulation analysis

This exploratory analysis was based on farming systems modelling, and requires further testing to explore the degree that maize management affects N responses. While maize density had a large impact on simulated yields, Peake et al. (2013) found that water extraction-rate parameters should be decreased at low plant populations, as high extraction-rate parameters at low densities can inflate simulated yield predictions (Peake et al. 2013). Although we did not adjust water extraction-rate parameters, at low maize densities responses to legume N were minimal; reflecting the low crop N demand due to low maize plant population. The forage legume model is also still under development, with further validation of biomass production and regrowth required (APSIM Initiative 2017). To improve this validation process, simulations should also be compared with on-farm forage legume production, not just research station and on-farm experiments. To address this uncertainty, a sensitivity analysis to a range legume inputs (1-6 t DM/ha) was used to determine potential maize yield responses

(Figure 4.4 and Figure 4.5). Simulated soil N mineralization was also higher than expected indicating that, while the soil N and surface organic matter models have been validated for legume leys in tropical environments (Probert et al. 1998), further validation of the decomposition and mineralization of legume residues is required. Finally, there has been limited validation of the on-farm performance and N responses for local maize varieties in West Timor, with validations by Hosang (2014) based on controlled field experiments rather than on-farm yields. Therefore, analysis indicates that legume N can substantially increase maize yield, however further testing is required to determine how management affects yield responses to additional N.

4.6. Conclusion

This simulation study found that forage legumes can significantly increase subsequent crop yield when all legume biomass is retained. However, spatial and temporal variability indicates that large and regular yield benefits are most likely to be achieved for sites and seasons with low levels of soil organic matter and where crops have sufficient yield potential to capture the benefit of forage legume N. Yet, realising these benefits will require shifts in other aspects of the production system and consideration of opportunity costs (land, labour etc.) of growing forage crops. Improved agronomic practice is critical to increasing maize yield potentials, with changes in crop plant density, intercropping intensity and weed control potentially required to maximise the value of additional N inputs. Importantly, weeds can be an important source of animal fodder (Nulik et al 2013), thus farmers' preferred management practices and the economic impact of controlling fallow weeds or using them for fodder requires evaluation. Redistribution of resources, including land and labour, to forage legume production may be required. These trade-offs for resource allocation can be minimised by farmers selecting a management option, such as a relay or rotation, that best fits their farming system properties. Benefits will also depend on biomass management; if farmers favour allocating shoot biomass to livestock instead of increasing soil N there is likely to be little or no yield benefit to the subsequent crop. Thus, large trade-offs exist in allocating biomass between farm enterprises unless farmers use options which can potentially provide dual soil N-fodder benefits, such as grazing or partial removal of legume biomass. Given the impact of legume biomass management and agronomic practice on subsequent yield benefits, further research is required to develop management options which provide dual soil N-fodder benefits, and how these benefits can be maximised depending on seasonal conditions.

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STATEMENT OF ORIGINALITY

We, the Research PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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5. Forage legume integration can increase whole-farm production and income in smallholder crop-livestock systems in West Timor, Indonesia

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5.1. Abstract

Rapidly rising demand for animal products in developing countries provides large economic opportunities for smallholder farmers. For crop-livestock systems, forage legumes are a strategy that offers the opportunity to increase livestock production as well as increase crop-livestock synergies and resource use efficiency. We examined the impact of forage legumes on fodder quality, whole farm income and downside risk for six case study farms in West Timor, Indonesia, using whole farm and participatory modelling. For each case study farm, we modelled a matrix which assessed: (1) four forage legume management options – i) maize-forage legume relay, ii) maize-forage legume rotation, iii) forage legume permanent stand on unutilised land and iv) a forage legume permanent stand replacing staple crops; (2) the area of forage legumes planted (0-1 ha) and (3) doubling bull production. Simulation outputs were then assessed by case study farmers to determine the options which best suited their socioeconomic and biophysical context. Results demonstrated that forage legumes can have large economic impacts, potentially more than doubling whole farm income. Legume management affected these net financial benefits, with large improvements in income and risk when forages did not replace staple crops but an increase in downside risk for little or no economic benefit when staple crops were replaced. The marginal value of feed increased with herd size from 0.9-1.0 M Rp/t TLU^{-1} (Tropical Livestock Unit, 250 kg liveweight) for smaller herds to 1.8-3.1 M Rp/t TLU^{-1} for larger herds. For small herds, there was no economic response if livestock were fed >0.6-0.9 t/TLU. Intensifying bull production without introducing forages increased downside risk with little upside benefit, however when both forages and bull production were intensified upside benefits and risk improved for larger herds. Although large economic benefits are achievable, participating farmers selected forage legume management options which the model indicated were economically sub-optimal, with farmer preferences achieving only 5-56% of the maximum simulated economic gains. Thus, forage legumes can have large economic benefits for smallholder farmers, however a better understanding of the production, economic and social impacts for a broader range of farmers are required so that forage legumes can fit within socio-economic constraints.

Additional keywords: farming systems model, forages, economics, food security, participatory modeling, intensification

5.2. Introduction

Rapidly increasing demand for livestock products in many developing countries, driven by rising incomes and increased urbanisation, provide significant economic opportunities for smallholder farmers. While resource-poor smallholder farmers currently supply the majority of milk and meat in tropical regions, they face large challenges in meeting the increasing demand for these products (Herrero et al. 2009). For mixed crop-livestock systems, which supply 60% of the meat in developing countries (Herrero et al. 2009), challenges to livestock intensification include balancing resource and input use while ensuring food security, continuity of rural livelihoods and sustainable natural resource management (Dixon et al. 2010). To illustrate, competing uses for crop biomass for fodder, food, fertiliser and fuel already constrain crop-livestock systems in South Asia; a region where cattle and buffalo numbers are expected to increase from 150 to 200 million by 2030 (Herrero et al. 2009). Land fragmentation, decreasing land per capita as well as infertile soils or degraded land also constrain the natural resources available to support livestock intensification (Thornton and Herrero 2015; Tittonell et al. 2009). Accordingly, sustainable intensification of crop-livestock systems requires smallholder farmers to produce more food and animal products without using more land, water or other inputs (Herrero et al. 2010).

One strategy for intensifying crop-livestock systems is the use of grass and legume forages (Bouwman et al. 2013; Herrero et al. 2010). This study focuses on herbaceous type legume forages and the potential production and economic impacts on smallholder crop-livestock systems. Forage legumes as a fodder or pasture offer opportunities to increase resource use efficiency and whole farm production as well as synergies between crop and livestock enterprises (Dalgliesh et al. 2010; Franzel et al. 2005; White et al. 2013). This includes contributing to key synergies such as increasing crop residues for livestock feed, manure for crop production, fodder for draft animals and reducing risks associated with income and food access (Dalgliesh et al. 2010; Giller et al. 2009; Herrero et al. 2010; White et al. 2013). However, the economic and social impacts of forage legumes can be positive or negative, and vary with socio-cultural, economic and agro-ecological factors (Giller et al. 2009; Sumberg 2002; White et al. 2013). Potential positive socioeconomic changes include increasing income, which in turn can be used to secure access to food (Giller et al. 2006), reduced cut and carry labour requirements (Connell et al. 2010), and reduced production and food security risk (White et al. 2013). At the same time, there are trade-offs including inequitable distribution of labour between men and women (Snapp and Silim 2002) and competition for land and labour resources with other crops which produce an economic yield for food or immediate sale (Giller et al. 2009). Given the suitability of livestock interventions is partly determined by relative labour and land costs (Baltenweck et al. 2003) as well as preferences and labour distribution (Waithaka et al. 2006), the contribution of forage legumes to livestock intensification is likely to vary between smallholder farmers.

There is considerable potential for forage legumes to contribute to increased livestock production in West Timor, Indonesia (Dalgliesh et al. 2010; Ngongo 2011). Dalgliesh et al. (2010) demonstrated that forage legumes could increase cattle liveweight gain, with male bali (*Bos javanicus*) calves gaining 220 g/day in the dry season compared with tethered-grazed animals which lost 64 g/day over the same period. Importantly, using forage legumes as an improved fallow, as proposed by Dalgliesh et al. (2010), also provides the opportunity to increase land and water use efficiency. This is particularly important given the decreasing land availability and increasing fragmentation occurring in West Timor (Ngongo 2011). Notably, improved forage technologies may enable smallholder farmers to take advantage of rapidly increasing cattle prices in Indonesia, along with Indonesian government policy identifying the province – East Nusa Tenggara – as a key region for meeting increased beef demand in Indonesia (Waldron et al. 2013). Despite these potential benefits and opportunities, the production and socioeconomic impacts of forage legumes at the farm level have not been assessed. Thus, further research is required to assess the compatibility of forage legumes with farmer's preferences, labour organisation and availability, as well as the economic feasibility including profitability and food self-sufficiency. Addressing these research gaps will help elucidate the potential impacts of forage legumes and their compatibility with crop-livestock farming systems in West Timor.

Despite the considerable potential of forage legumes to contribute to livestock intensification, adoption by smallholder farmers remains limited and, as a consequence, potential contributions to fodder, food and soil fertility remain low in smallholder farming systems (Giller 2001; White et al. 2013), including in Eastern Indonesia (Nulik et al. 2013). In fact, legume technologies are likely to occupy a niche within smallholder farming systems, rather than act as a broadly applicable option to livestock intensification (Elbasha et al. 1999; Ojiem et al. 2006; Sumberg 2002). Understanding the drivers which co-determine this potential niche in smallholder farming systems is critical to enabling targeted research and extension activities to engage with the most likely beneficiaries of forage legumes. At a farm level, this requires consideration of local agro-ecological, socio-cultural and economic factors (Ojiem et al. 2006), allowing system properties to be included in technology design rather than being considered as constraints to adoption (Sumberg 2002). Given the complex interactions between components of crop-livestock systems, whole farm and participatory modelling offer a way to explore a range of scenarios, identify interactions within the farming systems and quantify the potential biophysical and socioeconomic impacts (Giller et al. 2008; Thornton and Herrero 2001). Importantly, including participatory modelling allows contextualisation of scientific perspectives to local social and biophysical contexts (Sterk 2007). While a range of models have been developed to simulate smallholder farming systems (Giller et al. 2006; Groot et al. 2012; Herrero et al. 2007, van Wijk et al. 2014), the Integrated Analysis Tool (IAT) was selected as it is a dynamic model which uses long-term simulations to assess variability in whole farm production, household income and grain self-sufficiency, allowing us to test a range of potentially suitable options accounting for temporal variability (10 years of simulations) and spatial variability in agro-climatic conditions (six different locations). IAT is a whole farm model that integrates three separate modules: externally generated crop and forage inputs – which were generated using APSIM (Holzworth et al. 2014) – a Bali cattle growth module and smallholder economic module (Lisson et al. 2010). Importantly for this study, IAT was initially programmed to capture the distinctive features of Eastern Indonesian farming systems and has undergone participatory evaluation by Indonesian smallholder farmers (Lisson et al. 2010). Thus, IAT and participatory modelling were used to assess the agro-ecological and socioeconomic factors that influence the potential use of forage legumes in smallholder farming systems in West Timor and their likely biophysical and socioeconomic impacts.

Building on previous forage legume research in Eastern Indonesia (Nulik et al. 2013), this paper is an ex-ante assessment of the impact of integrating forage legume butterfly pea (*Clitoria ternatea*) into mixed crop-livestock systems for six case study farms in West Timor, Indonesia. The research quantifies the impact of forage legumes on fodder quality and livestock production and the subsequent impact on household income and grain production for a range of different forage legume management options. Thus, this paper uses whole farm and participatory modelling to identify the likely socio-ecological niche for forage legumes in West Timor and the potential economic impact for target farm types. We hypothesise that resource endowed smallholder farmers with bull fattening enterprises are likely to receive the largest benefit from forage legume intensification.

5.3. Methods

5.3.1. Research design

This study assessed a range of forage legume management and livestock intensification options and the potential trade-offs and impacts on livestock production, household income and food security. Six case study farms in West Timor, Indonesia, were characterised using a household questionnaire and resource flow diagram, the outputs from which were used to parameterise the whole farm model IAT. For each of these households, IAT was used to analyse a matrix that compared the impact of a range of options for integrating forage legumes into smallholder farming systems. Three factors were included in the matrix, with a total of 42 different scenarios run for each farm. The interactions between these three factors were assessed to determine whether they were additive (the impact equals the sum of the two interventions implemented separately) or synergistic (the impact was more than the two interventions implemented separately). The three factors analysed were:

1. Forage legume management and planting location

Given there are several ways to manage herbaceous forage legumes in crop-livestock systems (Dalgliesh et al. 2010), the impact of these options on household income and maize grain production were compared. The four management options were: (1) maize-forage legume relay, (2) maize-forage legume rotation, (3) forage legume permanent stand that replaces current maize crops and (4) forage legume permanent stand on unutilised land (Figure 5.1). All forage legumes were cut and used for cattle fodder as focus group discussions (Chapter 6) indicated that high quality fodder, not soil fertility, was likely to be the key driver of adoption.

2. Area of land allocated to forage legumes

The proportion of arable land planted to forage legumes was varied to determine the impact on cattle production, income and household food self-sufficiency. For the management options maize-forage legume relay, maize-forage legume rotation and a permanent stand replacing maize crops, the proportion of conventional maize replaced by each management option increased incrementally from 10, 20, 40, 70 to 100% of the area planted to conventional maize. For the relay, this meant that the area of maize remained constant but that intercropped cowpea was progressively replaced by forage legumes. For the rotation, half of the area allocated to the rotation was planted to forage legumes and half was planted to conventional maize, the balance was planted to conventional maize. For the permanent stand replacing maize, forage legumes progressively permanently replaced maize. The area planted to a forage legume permanent stand on unutilised land was determined by the availability of uncultivated land to a maximum of 1 ha (note that not all farms had unutilised land for legume production).

[redacted]

Figure 5.1 Forage legume management options for (a) maize forage legume annual rotation, (b) maize forage legume relay and (c) a permanent stand of forage legumes. Adapted from Nulik et al. (2013).

3. The number/proportion of bulls in the livestock enterprise

Intensifying bull production was simulated to determine the impact of doubling bull numbers on livestock production and income. The number of additional bulls was one for Uel, Oenai, Kesetnana and Manulai, two for Ekateta and three for Camplong. At all villages, the additional bulls were purchased at 150 kg for 0.028 M Rp/kg and sold at 250 kg for 0.032 M Rp/kg. These bulls were fed 5 kg DM/day based on estimates of amounts fed by farmers and dry matter intake by Dahlanuddin et al. (2014).

Simulations assessed the impacts of different combinations of these three factors on fodder quality, livestock production, household income and food self-sufficiency. Using a participatory approach, the case study households then evaluated the range of simulation outputs to identify those that best suited their preferences and resource availability.

5.3.2. Farm types and description of farming systems

5.3.2.1. Site selection and type

Building on previous forage legume research in West Timor (Dalgliesh et al. 2010), the research focused on Kupang and Timor Tengah Selatan (TTS) districts in West Timor, Indonesia. This area covers a range of farming systems and elevations, allowing us to test the robustness and performance of forage legumes in a range of environments. The area was divided into three elevations (Lowland 0-300m Above Sea Level (ASL), Midland 300-600m ASL and Highland >600m ASL), with two farmer groups selected at each elevation. These farmer groups were in villages Uel, Manulai No. 1 (Manulai), Ekateta, Oenai, Kesetnana and Camplong No. 2 (Camplong) (Figure 5.2). Each farmer group selected had a high proportion of members who owned cattle, high social capital, land available for legume production and cattle management that prevented crop damage from grazing animals (see Chapter 6 for more details). Within each farmer group, 6-10 households who owned ruminants or were interested in the non-fodder benefits of forage legumes, such as soil fertility and seed production, participated in on-farm legume evaluation activities (see Chapter 6). Of these households, one household was selected to participate in the bio-economic modelling activities described below. This household was selected by participating farmers as a representative household and farming system which they could use as a baseline to apply simulation outputs to their own farms. To check the degree that the 6 case study farms captured the range of farm types in the region, they were compared amongst a larger typology dataset collected from a short survey of 54 participating households (Chapter 6). Principle component and cluster analysis in R (version 3.2.4) using a previously described approach (Bidogeza et al. 2009; Hair et al. 2010; Tittonell et al. 2010) showed that the 6 farms were categorised into dryland subsistence focused farmers (Uel and Oenai), dryland livestock focused farmers (Ekateta and Kesetnana) and livestock focused farmers with both irrigated and dryland (Manulai and Camplong). However, as herd size was the key determining factor for farm types and the determinant of income from forage legumes, results presented below are grouped into small herds with 1 Tropical Livestock Unit (TLU, 250 kg liveweight; Uel and Oenai), medium herds with 1.4-2.1 TLU (Kesetnana and Manulai) and larger herds with 4-8.4 TLU (Ekateta and Camplong).

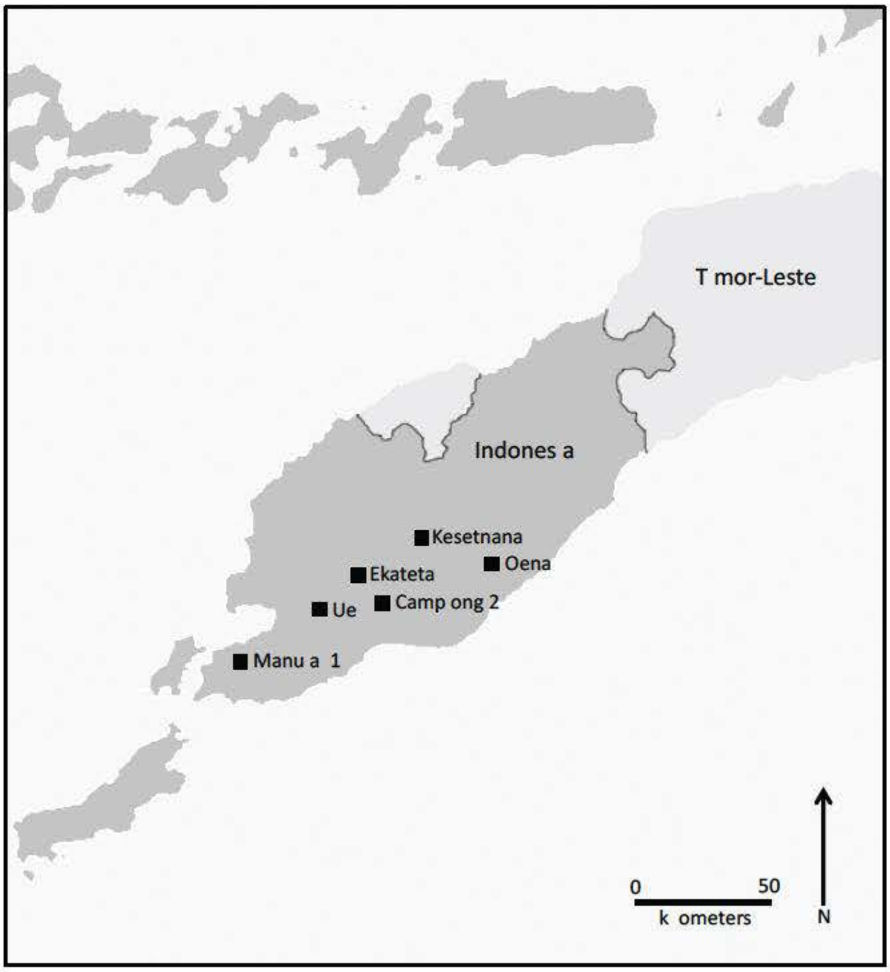

Figure 5.2. Map of West Timor, Indonesia, with the six research sites included in this study.

5.3.2.2. Case study farms

Each of the six households involved in whole farm modeling participated in a comprehensive questionnaire focusing on their household and farming system. The questionnaire collected information on household composition, education and labour availability; food security, household expenses, off-farm income and remittances; land ownership, location and soil types; annual and perennial crop production including inputs, labour requirements and yields as well as livestock ownership, contract fattening and management. Each household also constructed a resource flow diagram of their farming system that depicted farm configuration and the complex linkages and resource flows between agricultural enterprises and the household (Dorward et al.

2007). Participants first drew a map of their farm including major components such as their house, livestock, farming land, crops and common grazing land (Figure 5.3). They then drew arrows to indicate how key resources, such as crop residues and manure, moved between different parts of the farm, as well as explaining where farm products were sold and the resulting income. Following the questionnaire and resource flow diagrams, farm walks allowed visual observation and clarification of respondents' answers.

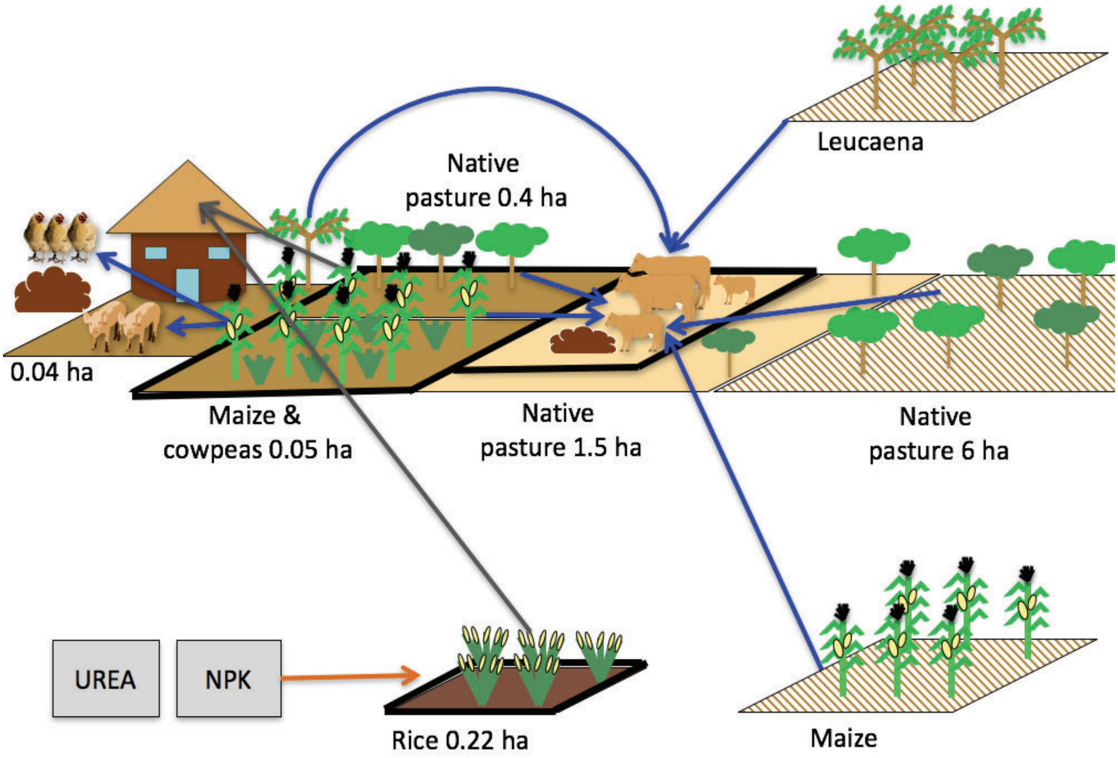

Figure 5.3. Example of a stylised resource flow diagram constructed by the case study household at Manulai. Blue lines represent fodder allocation; grey lines represent grain allocation and orange lines represent inputs. Land with diagonal lines represents land they do not own but can use to collect fodder.

Questionnaires and resource flow diagrams indicated there was considerable variation in the four resource pools – labour, land, forages and income – that are key for IAT analysis (Table 5.1). Labour availability ranged from 40 to 63 days/month, with Camplong farmers hiring additional labour for rice planting and harvest. Dry land area owned varied from 0.7 to 4.7 ha, with dry land utilisation (the % of land sown to food crops) ranging from 30 to 100%. Production of improved forages was mainly limited to small areas of king grass (*Pennisetum purpureum*) or leuceana (*Leucaena leucocephala,* <0.1 ha) except at Camplong and Uel where farmers had access 0.4-0.6 ha of leucaena. Income varied between farms for both agricultural (3.7-35.8 M Rp year^{-1}) and off-farm income (1.0-34.7 M Rp year^{-1}). Off-farm income was the most important source of income for half the households (Manulai, Uel and Ekateta). Although all households had sufficient income to cover their living expenses, after household costs were met, annual cash balance varied from +0.4 to +12.7 M Rp year^{-1}. Only two households (Camplong and Manulai) were increasing wealth on an annual basis. For the other households, low levels of cash and liquid assets left families vulnerable in emergency situations. No participants disclosed any loans or lines of credit.

5.3.3. IAT description and parameterisation

IAT was used to analyse the impact of forage legumes on livestock production, household income and food self-sufficiency and to test the sensitivity of these impacts to agro-climatic zone and farm management (Lisson et al. 2010, Mayberry et al. 2017). IAT is a whole farm model that simulates the interactions between biophysical and economic processes in smallholder farming systems (Figure 5.4).

Table 5.1. Characterisation of key biophysical and socio-economic attributes of six farming households for baseline parameterisation of IAT.

	Total land owned (ha)		*Un-used (ha)*	*Crops and forage (ha)*			*Livestock owned*		*Socioeconomic*					
Herd size	Dry land	Wet land	Dry land[A]	Maize	Rice	Forages	Total cattle (bulls)	TLU[C]	People living on farm	Labour (days/ month)	LLR[D]	House-hold income (M Rp/ year)	Cattle income (% total income)	Off-farm income (% total income)
Small														
Uel	2.00	-	0.60	0.4	-	0.35	1 (0)	1	2	43	1	47.9	4	72
Oenai	0.68	-	0.17	0.36	-	0.05	1 (0)	1	5	63	0.34	11.2	12	48
Medium														
Kesetnana	0.94	-	0.00	0.51	-	0.09	2 (1)	1.4	5	44	0.47	14.8	17	53
Manulai	1.99	0.22	1.50	0.05	0.22	0.05	4 (1)	2.1	6	40	3.13	27.1	11	86
Large														
Ekateta	1.93	-	1.42	0.45	-	0.06	6 (2)	4.1	3	60	0.96	22.1	25	34
Camplong	3.75	0.5	2.26	0.93	1.25[B]	0.56	9 (3)	8.4	4	60	2.5	28.1	60	3

[A] All wetland was used for annual rice production

[B] Farmers rent 0.75 ha of irrigated land for rice production

[C] Tropical livestock unit, 250 kg liveweight

[D] Land:labour ratio, the number of hectares of land per working family member (16-65 years)

The ruminant growth module uses standard livestock energy functions (CSIRO 2007) and field data have been used to calibrate these functions for Bali cattle production in Eastern Indonesia (Lisson et al. 2010, Mayberry et al. 2017). The economic module links output from crop, tree, forage and livestock production with non-farm activities through four key resource pools: labour, land type, fodder availability and finance. The resource endowment of the farming system under review is used to set the starting point of each resource pool. The interface combines these three modules where users make incremental changes in farm management to explore the impact of different options. For example, the area of forage legumes can be progressively increased in increments determined by the user, the impacts are then simulated in IAT after each incremental increase in forage legume area.

[redacted]

Figure 5.4. Schematic representation of the structure of the Integrated Analysis Tool (IAT) (Lisson et al. 2010).

5.3.4. Simulated crop and forage production

IAT uses externally simulated crop and fodder inputs that can be generated multiple ways, we used farming systems model APSIM (Holzworth et al. 2014) to simulate crop and forage production as it allowed us to account for climate variability and also to test forage and maize management options which farmers were not familiar with. Importantly, Gaydon et al. (2017) demonstrate that APSIM maize simulations, including simulations for West Timor (Hosang 2014), are within the bounds of experimental error. While APSIM's ability to simulate tropical forage legumes has been tested in northern Australia (Hill et al. 2006), further development and validation of the APSIM tropical forage legume models is currently underway (APSIM Initiative 2017).

Simulations used solar radiation (MJ/m^2), daily temperature (°C) and daily precipitation (mm) from government meteorological stations Naibonat (123°50'40"E, 10°05'49"S) for lowland and midland sites and Oenali (124°19'15"E, 9°52'51"S) for highland sites. Simulations used previously characterised soils that are available in the APSOIL database (Dalgliesh et al. 2012) (Table 5.2). At each site, soil samples were also analysed for pH and organic carbon (OC). This chemical analysis was combined with APSOIL data to characterise the soils for each site. More detailed climate and soil chemical analysis is presented in Chapter 4.

Table 5.2. Plant available water capacity (mm, PAWC) to 1.8 m depth for a range of key crops and forages for four soils characterised in West Timor, Indonesia, which represent the soil types at six villages. PAWC was determined using the APSOIL database (Dalgliesh et al. 2012).

		Plant available water capacity (mm)						
Soil	Farm/s	Maize	Rice	Mung-bean	Cow-pea	Pea-nut	Butter-fly pea	Bambatsi grass
Shallow Alfisol	Ekateta	88	88	71	86	86	164	164
Alfisol	Camplong Oenai	105	105	74	101	101	194	194
Vertosol	Manulai Kesetnana	133	133	89	103	103	210	210
Incep-tisol	Uel	165	165	123	148	148	222	222

Grain and stover yield for rice, maize, cowpea, mungbean and peanuts and forage production for bambatsi, leucaena, butterfly pea and native pasture were simulated for each location from 2001 to 2010 using APSIM. Grain crop simulations used varieties that had representative growing season length, and yields and nitrogen (N) applications based on those reported by farmers. Dry land crops were sown after 15 December and 15 mm of rainfall, rain fed rice after 25 December and 20 mm of rainfall, and irrigated rice was transplanted on 10 January. To reflect local agronomic practices, maize was planted at 4 plants/m^2, intercropped cowpeas at 1 plant/m^2, mung beans at 2 plants/m^2, rain fed rice at 120 plants/m^2 and irrigated rice 75 plants/m^2. As forage legumes do not increase maize grain yields at low maize crop densities or under sub-optimal weed management (Chapter 4), IAT simulations used maize yields for the baseline simulations described above for all scenarios analysed (Table 5.3).

Table 5.3. Long term simulated mean maize yield when intercropped with cowpea and baseline forage dry matter (DM) production after an agronomic efficiency factor of 0.6 has been applied. Range is presented in parenthesis.

	Maize (t/ha/year^{-1})				Baseline forages (t DM/ha year^{-1})			
	Grain		Stover		King grass		Leucaena	
Lowland								
Manulai	2.1	(1.4-2.7)	6.1	(4.9-7.7)	*		1.3	(1.0-1.8)
Uel	1.7	(1.0-2.6)	4.9	(3.9-6.3)	*		1.3	(1.0-1.8)
Midland								
Ekateta	1.4	(0.1-2.1)	4.9	(3.5-6.8)	4.5	(3.5-6.5)	0.9	(0.7-1.3)
Camplong	1.9	(0.4-2.7)	5.4	(4.2-7.6)	4	(3.5-5.0)	0.8	(0.7-1.0)
Highland								
Oenai	0.7	(0.2-1.6)	2.2	(1.6-3.3)	*		0.6	(0.4-0.8)
Kesetnana	1.1	(0.4-2.4)	5.2	(2.8-6.3)	5	(4.0-6.5)	1.0	(0.8-1.3)

*Not grown

Forage legume production was simulated for three different management options; (i) forage legume-maize relay, (ii) forage legume-maize annual rotation and (iii) forage legume permanent stand using the APSIM-Butterfly pea model (Figure 5.1, Holzworth et al. 2014). For the butterfly pea-maize relay, butterfly pea was planted inter-row with maize (4 plants/m^2) at maize anthesis (15 February) at 20 plants/m^2, after maize harvest butterfly pea biomass was then cut and removed at 25 mm above ground level every 2 months (3 April, 3 June and 3 August). Legumes were terminated on 4 August. For the butterfly pea-maize rotation, butterfly pea was planted at 15 plants/m^2 on 1 February and then managed as described for the relay. The permanent stand of butterfly pea was also planted at 15 plants/m^2 on 1 February and cut and removed on the same dates however, as the simulation didn't account for decreased productivity over time, annual dry matter production was multiplied by a factor of 0.8 in years 4 and 5, after which a new stand of butterfly pea was established (Table 5.4). As APSIM doesn't have modules for other forage inputs we adapted similar modules in order to derive predictions of biomass production in response to climate variability. King grass was simulated using the APSIM-bambatsi model planted at 1 plant/m^2 and 90% of biomass was harvested when green biomass was above 3 t/ha. To reflect local production levels measured by Budisantoso et al. (2004), leucaena production was estimated by multiplying bambatsi grass dry matter production by 0.2 which resulted in average dry matter production of 0.9 t dry matter (DM)/ha across sites, this is lower than the 2.8 t DM/ha average cumulative leaf production for *Leucaena leucocephala* c.v. Taramba because low productivity varieties of leucaena are still grown on-farm and suboptimal management and low plant populations result in lower dry matter production (Budisantoso et al. 2004). Native pasture simulations also used the APSIM-bambatsi model planted at 1 plant/m^2 however, 90% of biomass was only harvested when green biomass was above 10 t/ha.

Table 5.4. Long term simulated mean butterfly pea dry matter (DM) production when grown in a maize-forage legume relay, maize-forage legume rotation or as a permanent stand after an agronomic efficiency factor of 0.6 has been applied. Range is presented in parenthesis.

	Forage legumes (t butterfly pea DM/ha year^{-1})					
	Relay		Rotation		Permanent	
Lowland						
Manulai	2.4	(1.2-3.5)	4.7	(3.6-5.7)	4.1	(3.0-5.8)
Uel	2.6	(1.6-3.8)	4.8	(4.2-5.5)	4.2	(3.1-5.7)
Midland						
Ekateta	1.8	(0.7-2.4)	3.7	(2.9-4.3)	3.2	(2.0-4.5)
Camplong	1.8	(0.5-2.9)	3.7	(3.1-4.7)	3.3	(2.2-4.7)
Highland						
Oenai	2.7	(2.2-4.1)	4.8	(4.3-6.5)	4.4	(2.3-5.9)
Kesetnana	3.4	(2.3-4.8)	6.1	(3.8-6.7)	5.6	(2.3-6.1)

APSIM simulations commonly represent optimal growing conditions and crop management practices and have a limited ability to simulate intercropping of multiple crops (Carberry et al. 1994), such as the range of crops that are intercropped with maize in West Timor (Ngongo 2011). Consequently, simulations can over-predict grain yield or, in the case of intercropping, can potentially underestimate yield of some crops when more than two crops are grown together. APSIM validation by Hosang (2015) indicated that correlation between observed and predicted maize grain yield for cultivars characterised for West Timor was 0.97 (R^2). However, this correlation used a research station experiment with maize yielding 1.9-2.7 t/ha with no fertiliser applied. Estimated yields for participants in this project shows that farmer yields were a maximum of 60% of the yields obtained in APSIM (Chapter 4). This is consistent with other APSIM validations where smallholder grain yields are 70% of the yields obtained in APSIM (Liang et al. 2006). Consequently, an agronomic efficiency factor of 0.6 was applied to grain, stover and fodder outputs simulated by APSIM (Table 5.3 and Table 5.4). While there was no formal model evaluation, sensibility testing of APSIM and IAT simulation outputs with each case study household by discussing simulation results indicated that baseline yields and livestock production were within expected levels.

5.3.5. Simulated livestock production

To simulate livestock production, cattle were fed using current grazing and cut and carry management practices (Chapter 6). The model allocated forages from various sources into four forage pools: (1) legume biomass including cowpea and mungbean stover, and forage legumes (including leucaena), (2) king grass, (3) cereal crop residues and (4) native pasture. Feeding priority was assigned for each forage pool, with forage legume biomass, leucaena, cowpea and mungbean stover allocated the highest priority followed by king grass, cereal crop stover and native grass. Consumption of legumes was set to maximum of 30% of the diet, all other forage pools could be fed at 100% of the diet. Given the structure of the livestock module, all cattle were fed the same diet, including forage legumes when they were included in the scenario analysis. Although not formally evaluated, the model has previously been calibrated for Bali cattle (Lisson et al. 2010). Baseline liveweight changes and responses to forage legume supplementation were also compared to previous experiments (Dalgliesh et al. 2010; Nulik et al. 2013), farmers' descriptions of seasonal liveweight (LW) changes (Chapter 6) and sensibility tested with participating households.

5.3.6. Input costs and commodity prices

Crop and forage input costs and commodity prices used were based on farmer information. Hired labour, which was used for rice production, cost 0.09 M Rp/day, glyphosate cost 0.07 M Rp/L, pesticide cost 0.13 M Rp/L, urea cost 0.05 M Rp/kg and NPK 0.06 M Rp/kg. Inputs reflected farm practice, with maize inputs only used at Kesetnana, where 88 kg urea/ha was applied. In comparison, all farmers that grew rice applied 400 kg urea/ha, 150-250 kg NPK/ha, 1-2 L glyphosate/ha and 0-1 L pesticide/ha. Maize grain was valued at 0.005 M Rp/kg, rice at 0.01 M Rp/kg and mungbeans 0.01 M Rp/kg. For livestock, costs were 0.01 M Rp/month for veterinarian services, 0.01 M Rp/month for tethering rope and 0.02 M Rp/month for transport. Market value was determined through discussion with cattle traders and was set at 0.020 M Rp/kg for suckling animals, 0.024 M Rp/kg for female calves and breeding cows, 0.028 M Rp/kg for male calves and weaners, and 0.032 M Rp/kg for bulls at 250 kg or greater, the minimum sale weight for export to Java (Waldron et al. 2013).

5.3.7. Participatory forage legume scenario analysis

Participating households, who had been testing forage legumes on their farms for two years (Chapter 6), selected the most suitable forage legumes scenario for their farm by assessing IAT scenario outputs for the 42 different scenarios described above. Scenario outputs were assessed using the resource flow diagram, which was developed by the household, printed on a large piece of paper. Using this image of the farm, paper tokens with pictures of maize grain, money and forage legumes were placed on the large piece of paper to represent outputs for each IAT simulation. Thus, starting with the baseline scenario, farmers were able to use these tokens to visually represent the area of forage legumes, maize production and household income as indicated by the outputs for each simulation. These tokens were then added or removed as each of the scenarios simulated in IAT was evaluated by the household. For each different scenario farmers assessed the potential positive and negative impacts on crop and livestock production, income, risk, labour and food security. As this was an ex-ante study, labour requirements were evaluated using farmers' insights rather than IAT outputs as farmers were unable to quantify labour inputs for legume production in sufficient detail for the model. After evaluating the range of scenarios, farmers eventually selected a management option and area that best suited their individual production objectives and resource availability.

5.4. Results

5.4.1. Farm feed base

Farmers relied heavily on native pastures, with IAT simulations indicating native pasture in baseline scenarios accounted for 42-82% of fodder consumed by cattle. At Camplong simulations indicated 23 t native pasture DM year^{-1} was required to feed 10 TLU, which was considerably more than at Ekateta (6 t DM year^{-1}), Manulai (6 t DM year^{-1}), Kesetnana (4 t DM year^{-1}), Uel (1 t DM year^{-1}) and Oenai (1 t DM year^{-1}). This heavy reliance on native pastures was due to a lack of forages and crop stover, which was sufficient to provide fodder for only 1-5 months. Importantly, intake of high quality fodder such as leucaena and grain legume stover was also low, with <15% of legume DM in baseline diets for all farms: Kesetnana (13%), Uel (9%), Oenai (8%), Ekateta (7%), Camplong (4%) and Manulai (1%).

A permanent stand of forage legumes had the largest impact on legume intake as it produced more biomass than a relay and didn't replace grain crops, which are a source of fodder (Figure 5.5). However, the land available for establishing legumes varied at each site, thus at some sites under some management options the recommended 30% legume intake (Nulik et al. 2013) could not be achieved for the entire year. Larger herds (>8 TLU) were unable to achieve annual dietary intake of one third legumes with ≤1 ha of forage legumes, while medium herds (4 TLU) required 1 ha of forage legumes and smaller herds (≤2 TLU) <0.3 ha of forage legumes to meet this target. Across the six farms, 0.5-1 t legume DM year^{-1} was required per TLU to achieve 30% legume in the diet over the whole year.

Notably, there was a linear response in livestock income to increasing the proportion of legume in the diet up to 30%. Importantly, this economic response increased with increasing herd size. To illustrate, for a herd with 8 TLU, each 1% increase in the amount of legume in the diet up to 30% resulted in an additional 1 M Rp year^{-1}, while each 1% increase in legume consumption for a herd of <2 TLU increased income by 0.04-0.1 M Rp year^{-1}. Thus, the marginal return for a large herd (8 TLU) was 0.1 M Rp/TLU for each 1% increase in legume in the diet compared to 0.04-0.07 M Rp/TLU for herds with <2 TLU.

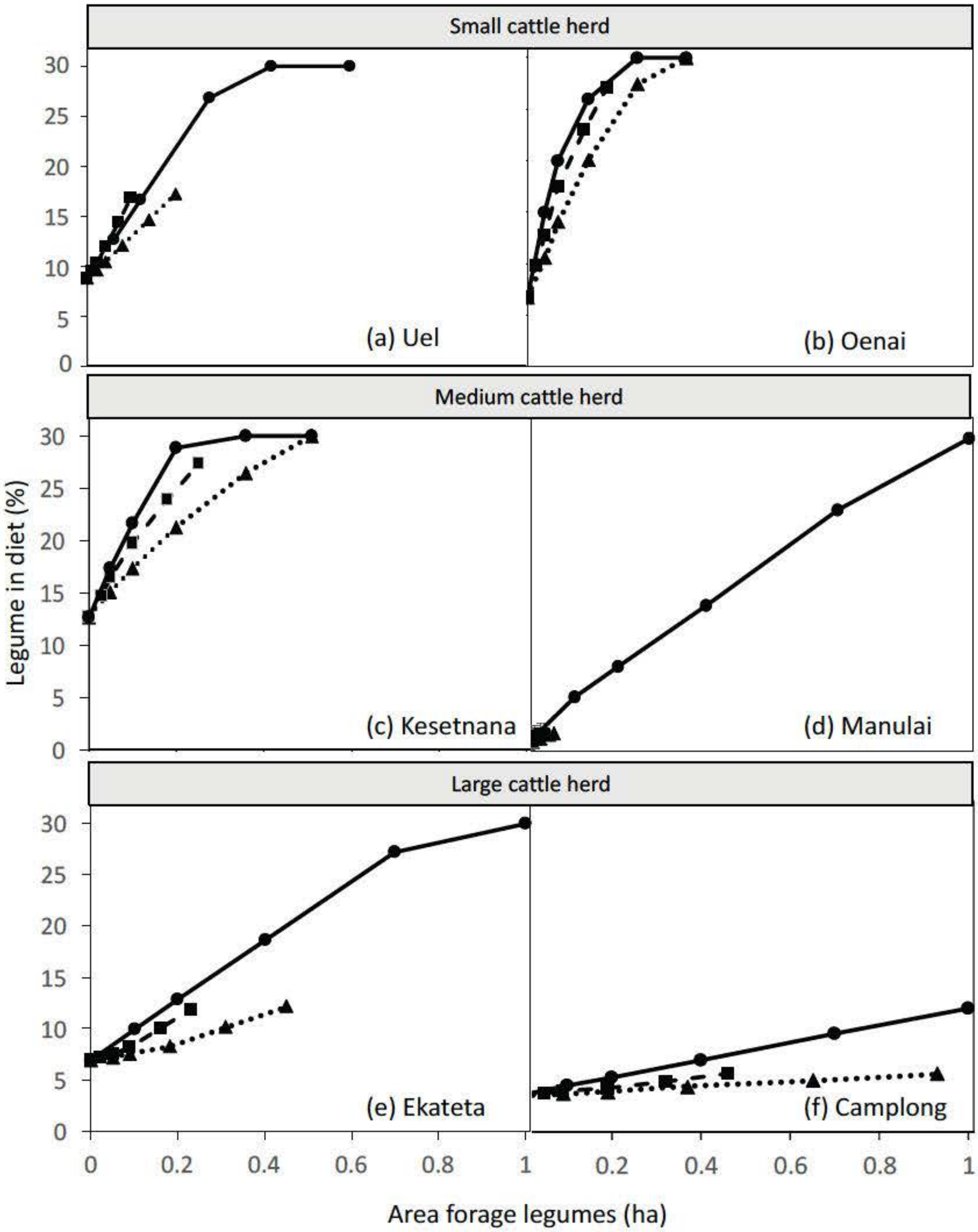

Figure 5.5. Change in the mean annual dietary intake of legume biomass as percentage of total diet in response to increasing areas of forage legumes when legumes are planted as a maize-legume relay (dots, triangle), maize-legume rotation (dashes, square) or a permanent stand (solid, circle) for six case study farms in West Timor, Indonesia.

5.4.2. Livestock production and income for case study farms

Baseline simulations indicated that, for the six case studies, livestock turn-off varied from 58-940 kg LW year^{-1}, with bull sales accounting for only 44-61% of baseline livestock sales (Table 5.5). Given bulls are commonly sold when >250 kg LW (Waldron et al. 2013), not all farmers sold cattle each year. Average net whole herd income ranged from 1.4-3 M Rp year^{-1} for herds with ≤2 TLU and 5.7-20.3 M Rp year^{-1} for herds >4 TLU.

To examine the impact of legume integration into the various farms, scenarios introducing 0.4 ha permanent stand of forage legumes were assessed, as this was the largest area available for forage legumes for all case studies and a permanent stand had the largest impact on dietary intake (Figure 5.4). Amongst the 6 farms, introduction of 0.4 ha of forage legumes increased calves born by only 0-0.1 year^{-1} when farmers had 1 TLU but by 0.4-0.8 year^{-1} for medium and large herds (1.4-8 TLU) (Table 5.5). While forage legumes (0.4 ha) increased total cattle sales on all farms by 22-157 kg LW year^{-1} (17-107%), net livestock income increased by only 0.6-1.6 M RP year^{-1} (55-114 %) for smaller herds (≤2 TLU) compared to 2.9-4.4 M Rp year^{-1} (22-103 %) for larger herds (>2 TLU). Importantly, the response per TLU to 0.4 ha of forage legumes decreased with increasing herd size, with a net increase in income of 0.5-0.7 M Rp/TLU for large herds compared to 1.1-1.6 M Rp/TLU for smaller herds. The impact of legume integration on whole farm and total household income varied depending on production responses and reliance on off-farm income. Where baseline legume intake was low (Manulai), there was a large response in livestock production which increased whole farm income by 84%. In comparison, whole farm income increased by only 8-26% for the other case study farms.

Doubling bull ownership without introducing forage legumes increased livestock sales by 112-188 kg LW year^{-1} (Table 5.5). This equated to a 140-280% increase in livestock sales for small herds (≤2 TLU) but only 20-131% for larger herds, as baseline sales for large herds were already high. Importantly, doubling bull numbers increased the percentage of bulls sold from 44-61% to 70-85% of total sales. Consequently, bull intensification had a larger impact on total cattle sales than forage legumes but the cost of purchasing bulls meant doubling bull numbers increased net livestock income by only 9-70%, compared to 22-103% for 0.4 ha of forage legumes. Notably, doubling bull ownership also decreased calves born by 0.2-0.6 year^{-1} for large herds (Camplong and Ekateta), although there was no impact for other farms where there were smaller herds and less competition for fodder.

Simultaneously intensifying forage legume and bull production increased income by 3 M Rp year^{-1} for smaller herds (<2 TLU) and by 4.8-6.7 M Rp year^{-1} for larger herds (>2 TLU). There was a small synergistic interaction between legume and bull intensification for both total livestock sales and net income. To illustrate, at Uel individually introducing forage legumes increased total cattle sold by 42 kg LW year^{-1} and doubling bulls increased sales by 156 kg LW year^{-1}, when legume and bull production were simultaneously intensified livestock sales increased by 233 kg LW year^{-1}, which is 35 kg LW year^{-1} higher than if there was no synergistic benefit. For total cattle sales, this synergistic interaction resulted in an additional 1-35 kg LW year^{-1} sold at Uel, Manulai and Kesetnana but no additional sales for other case study sites (Table 5.5). A synergistic benefit was also evident for net livestock income, with the synergistic interaction increasing income by 0.1-1 M Rp year^{-1} at all villages except Ekateta.

Table 5.5. Livestock production and farm income increases due to forage legume introduction (0.4 ha) and doubling bull ownership alone and in combination. Scenarios with 0.4 ha permanent stand of forage legumes were used as a permanent stand had the greatest impact and 0.4 ha could be planted on all six case studies farms in West Timor, Indonesia. Average values are presented, percentage increase from baseline shown in parenthesis.

		Births	*Beef turn-off*			*Income*			
Farm	Scenario	Calves born (Calves /yr)	Total cattle sold (kg LW/yr)		Bulls sold (kg LW/ year)	Livestock net income (M Rp/yr)		Whole farm income (M Rp/yr)	
			kg	Δ (%)*	kg	M Rp	Δ (%)	M Rp	Δ (%)
Small cattle herd (1 TLU)									
Uel	Baseline	0.5	88		41	2.0		13.3	
	+ Legumes	0.6	130	(48)	67	3.1	(55)	14.4	(8)
	+ Bulls	0.5	244	(177)	198	2.9	(45)	14.2	(7)
	+ Legumes + Bulls	0.6	321	(264)	259	5.0	(150)	16.3	(23)
Oenai	Baseline	0.5	58		26	1.4		5.8	
	+ Legumes	0.5	80	(38)	39	3.0	(114)	7.4	(28)
	+ Bulls	0.5	202	(248)	169	1.9	(36)	6.3	(9)
	+ Legumes + Bulls	0.5	222	(282)	181	4.4	(214)	8.5	(47)
Medium cattle herd (1-2 TLU)									
Kesetnana	Baseline	0.6	101		65	2.6		7.0	
	+ Legumes	1.0	172	(70)	113	4.4	(69)	8.8	(26)
	+ Bulls	0.6	242	(140)	206	3.1	(19)	7.5	(7)
	+ Legumes + Bulls	1.0	324	(221)	265	5.2	(100)	9.6	(37)
Manulai	Baseline	0.5	109		54	3.0		3.7	
	+ Legumes	1.3	226	(107)	123	6.1	(103)	6.8	(84)
	+ Bulls	0.5	307	(182)	254	5.1	(70)	5.8	(57)
	+ Legumes + Bulls	1.1	425	(290)	337	8.3	(177)	9.0	(143)
Large cattle herd (4-8 TLU)									
Ekateta	Baseline	1.4	252		139	5.7		14.7	
	+ Legumes	1.8	364	(44)	207	8.6	(51)	17.6	(20)
	+ Bulls	1.2	583	(131)	486	8.2	(44)	17.2	(17)
	+ Legumes + Bulls	1.5	671	(166)	543	10.5	(84)	19.5	(33)
Camplong	Baseline	4.3	940		527	20.3		27.3	
	+ Legumes	5.0	1,097	(17)	686	24.7	(22)	31.7	(16)
	+ Bulls	3.7	1,128	(20)	794	22.1	(9)	29.1	(7)
	+ Legumes + Bulls	4.5	1,234	(31)	847	27.0	(33)	34.0	(25)

*Indicates percentage change from the baseline

The impact of forage legumes and bull intensification on financial risk reflects changes in production risk and provides an insight into the impact of these interventions on household financial risk. Introducing only forage legumes (0.4 ha) increased the upside benefit, increasing the maximum net income for 10 years of simulations by 1.4 M Rp year^{-1} (Uel) to 7.1 M Rp year^{-1} (Camplong) (Figure 5.6). Importantly, a forage legume permanent stand did not increase downside risk (exposure to unanticipated low outcomes) for any farms. In contrast, doubling bull ownership without introducing forage legumes increased downside risk for small and medium herds, with minimum livestock income reduced by 3.4–3.5 M Rp year^{-1} across these farms. At the same time, doubling bull ownership decreased downside risk for large herds (4-8 TLU), which had sufficient baseline livestock income to cover the costs of purchasing bulls; increasing minimum net livestock income from 0.8-6.7 M Rp year^{-1} to 2.8-10.5 M Rp year^{-1}. Although doubling bulls increased downside risk for small and medium sized herds, it also increased the upside benefit for all herds, increasing maximum income by 0.3-1.5 M Rp year^{-1}.

Intensifying both forage legume and bull production in combination, increased downside risk for herds with <2 TLU (Oenai, Uel and Kesetnana) but decreased downside risk for herds with >2 TLU (Manulai, Ekateta and Camplong). Hence, for smaller herds, doubling bull numbers has similar levels of downside risk whether or not forage legumes are introduced. Despite this, introducing both legumes and additional bulls had a larger upside benefit than intensifying just legume or bull production for all farms, except Camplong. Compared to the baseline, intensifying forage legumes and bull production together increased maximum income for all farms by 1.5-5.3 M Rp year^{-1}. Importantly, this meant that for herds with <2 TLU introducing both legume and bulls increased risk but also increased upside benefits, while for herds with >2 TLU financial risk decreased and upside benefits increased.

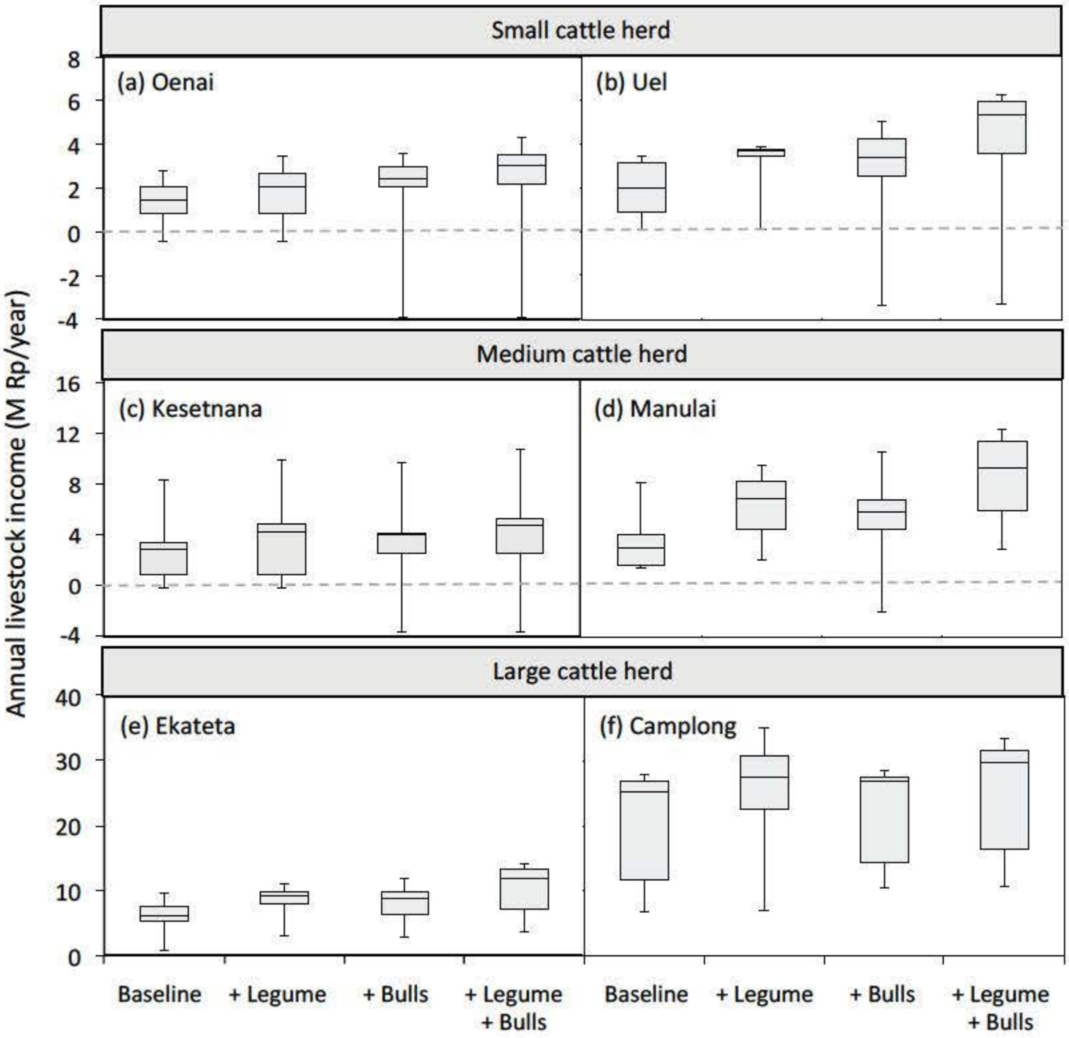

Figure 5.6. Variation in annual livestock income for 10 years of simulations for baseline production, baseline plus an additional 0.4 ha of forage legumes (+ Legume), baseline plus double bull ownership (+ Bulls) and baseline plus both 0.4 of forage legumes and double bull ownership (+ Legumes + Bulls) for small (1 TLU), medium (1.4-2.1 TLU) and large (4-8.4 TLU) herds. The boxes represent the lower and upper quartiles and median annual livestock income, whiskers represent maximum and minimum income for 10 years of simulations.

5.4.3. Forage legume area and bull numbers affect income

Increasing the area of forage legumes increased average annual income and upside benefits across all farm types. However, there was a larger economic response to increasing areas of forage legumes for herds with >2 TLU (Manulai, Ekateta and Camplong) than for herds with <2 TLU (Uel, Kesetnana and Oenai). For equivalent areas of forage legumes, there was a larger increase in net income for herds with >2 TLU (Figure 5.7). However, at Manulai (2.1 TLU), the economic benefit plateaued above 0.7 ha, indicating there was little additional economic benefit of planting an additional 0.3 ha to reach 1 ha of forage legumes. A similar trend was evident at for small herds (1 TLU), with little or no economic response above 0.3 ha of a permanent stand of forage legumes, as the 30% threshold for legume intake had been reached (Figure 5.5). Thus, for herds with 1 TLU, 0.3-0.4 ha of forage legumes are required to maximise economic returns at 1-1.6 M Rp year^{-1}, or 3.3-4.0 M Rp ha^{-1} year^{-1}. In comparison, for herds with >2 TLU 0.7-1 ha was required to achieve the maximum net return of 6-7 M Rp year^{-1} under current land constraints, or 6-7 M Rp ha^{-1} year^{-1}. Importantly, upside benefits of forage legumes increased with increasing area. To illustrate, at Camplong maximum annual income for ten years of simulations increased by 1.6 M Rp year^{-1} for 0.1 ha compared to 28.8 M Rp year^{-1} for 1 ha forage legumes. Notably, there were only small reductions in downside risk for large areas (≥0.7 ha) of forage legumes, with 1 ha of forage legumes at Camplong increasing minimum annual income by 0.9 M Rp year^{-1}.

The economic response to increasing areas of forage legumes increased when bull numbers doubled. However, for low areas of forage legumes the effect of intensifying both legume and bull production was additive, with synergistic effects only evident at some sites when larger areas of forage legumes were planted. This indicates that a synergistic effect is only achieved when there is sufficient forage legume DM to take advantage of the economic opportunity provided by doubling bull ownership. Importantly, the economic benefit of this synergistic relationship commonly provided a greater economic benefit for larger herds (>2 TLU) than small herds (1 TLU). Importantly, increasing areas of forage legumes did not alleviate the downside risk from doubling bull numbers for small and medium herds (data not presented).

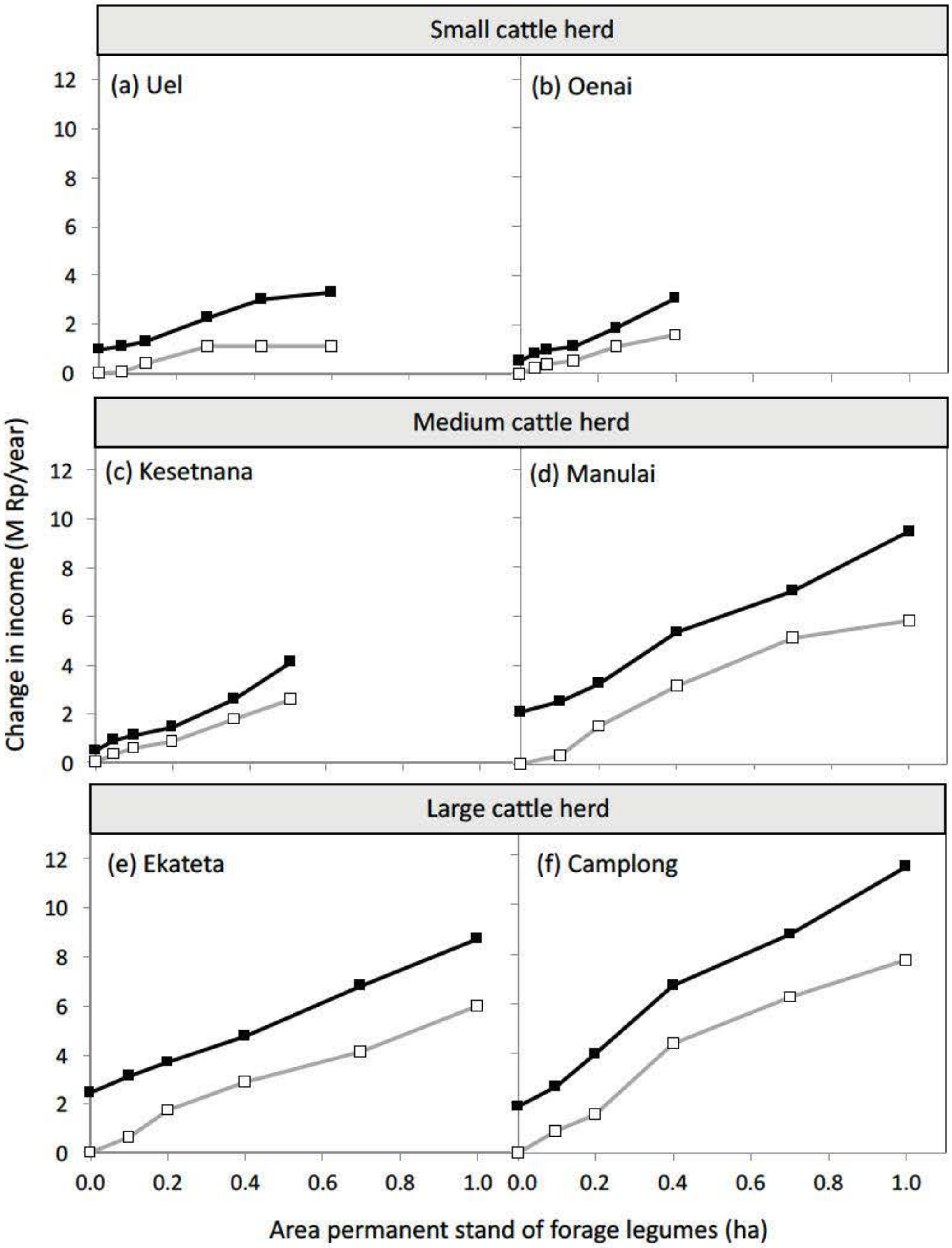

Figure 5.7. Change in net income (M Rp/year) in response to increasing areas of a forage legume permanent stand for baseline herd size (white squares) and baseline herd size + double bull numbers (black squares) for six farms in West Timor, Indonesia with small (1 TLU), medium (1.4-2.1 TLU) and large (4-8.4 TLU) herds.

While Figure 5.7 assessed the economic response for the whole herd, this does not account for variability in livestock numbers and legume productivity differences amongst the 6 case study farms. Figure 5.8 shows that the response to the amount of biomass allocated per TLU was distinctly different for smaller and larger herds. The marginal value of feed, which is a factor of both feed supply and demand (Bell et al. 2008), was 1.8-3.1 M Rp/t TLU^{-1} for larger herds (>2 TLU) compared to 0.9-1.0 M Rp/t TLU^{-1} for smaller herds (≤2 TLU). Importantly, the baseline legume intake from tree and grain legumes was commonly lower for herds with >2 TLU (1-7% baseline dietary legume intake) than herds with ≤2 TLU (8-13% baseline dietary legume intake) resulting in a larger economic response to forage legumes driven by both an increase in reproductive rates and livestock sales (Table 5.5). Thus, there is a larger financial benefit for larger herds (>2 TLU) than smaller herds (≤2 TLU) for the equivalent amount of legume biomass.

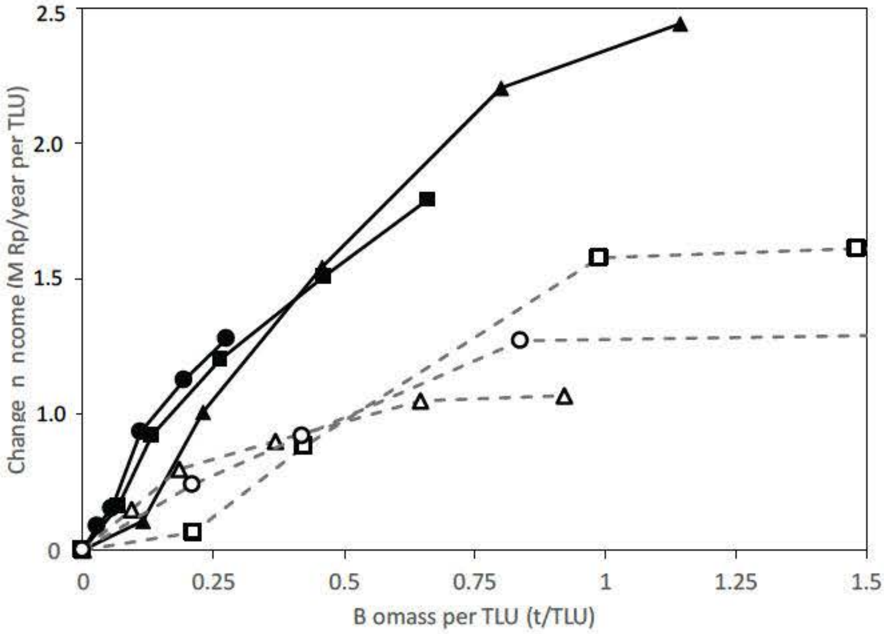

Figure 5.8. Change in net income per tropical livestock unit (TLU) in response to increasing amounts of forage legume biomass allocated to 1 TLU for baseline herds for six case study farms (Herds with <2 TLU [dashed line]: Uel, white square; Kesetnana, white circle; Oenai, white triangle; Herds with >2 TLU [solid line]: Manulai, black triangle; Ekateta, black square; Camplong, black circle) in West Timor, Indonesia.

5.4.4. Forage legume management affects income and food security

Not all farmers have spare land and hence systems where legumes are integrated with maize as a rotation, relay or replacing maize were evaluated. For these options, it is important to understand how they may impact the economic benefit once the impact on staple food crops are considered. Replacing maize had a large negative impact on farm returns, with net financial losses or limited economic benefits experienced across all farms (Figure 5.9). This was particularly important for herds with 1 TLU (Uel and Oenai), as the increase in livestock income from introducing forage legumes didn't cover the cost of maize grain replaced by legumes. In fact, if all the maize was permanently replaced with forage legumes, average annual farm income was reduced by 23% at Uel and 52% at Oenai. Hence, forage legume systems that maintain or increase maize production are best. Consequently, relays performed better economically than if maize was displaced by a permanent stand or a rotation.

However, if spare farm land is available then this could be used for a permanent stand, which has a larger economic benefit because more legume biomass is produced per hectare than for a relay. To illustrate the impact on income, at Camplong for 0.9 ha of forage legumes, a permanent stand on unutilised land increased income by 7.1 M Rp year^{-1}, while a relay increased it by only 3.9 M Rp year^{-1}. Consequently, differences in land availability across the farms meant that a permanent stand on unutilised land offered the maximum potential increase in net income at Uel, Manulai, Ekateta and Camplong while at Oenai and Kesetnana, where land availability is limited, a relay was the best option. Thus, the best economic option for introducing forage legumes into crop-livestock systems depends on land availability.

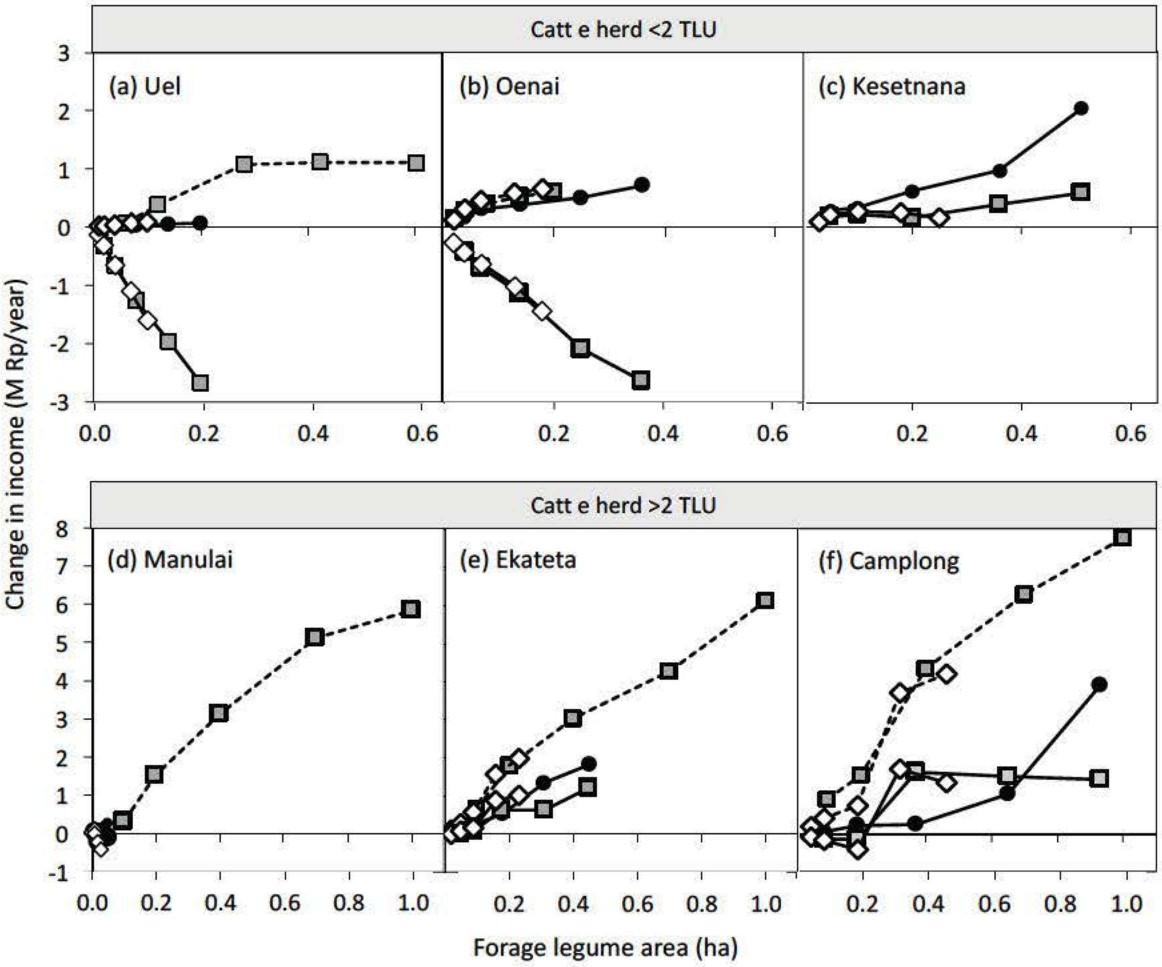

Figure 5.9. Impact of legume management and area on net income accounting for losses in maize production when legumes are used on unutilised land (- - - -) or are integrated into land allocated to maize (——) for six case study farms in West Timor, Indonesia. Management options were a relay (circle), rotation (diamond) and permanent stand (square).

5.4.5. Participatory scenario evaluation

Across the six case study farms, farmers did not favour the most profitable simulated option. Rather, labour constraints meant they preferred smaller areas of forage legumes, while their production system, land and labour availability determined what was considered the most suitable management option (relay, rotation or permanent stand). Farmers with >2 TLU and ≥1 ha of unutilised land (Camplong, Ekateta and Manulai) favoured establishing a permanent stand of forage legumes on unutilised land to maximise economic benefits, minimise labour inputs by only replanting every five years, as well as to use infertile land (Table 5.6). At Camplong, farmers elected to plant 0.4 ha of forage legumes which increased net income by 4.4 M Rp year^{-1}, which was 56% of the maximum simulated financial benefit of forage legumes. Notably, this increased whole farm income by 16% when just forage legumes were introduced, and by 26% when bull numbers were also doubled. In comparison, at Ekateta and Manulai farmers only wanted to plant 0.1 ha, which resulted in a net increase in income of only 5-13% of the maximum financial benefit that could be achieved by planting 1 ha of forage legumes. Importantly, this financial benefit only increased whole farm income by 5-8%, with additional bulls required to achieve a 26-68% increase in whole farm income.

At other farms, land constraints meant farmers chose forage legumes options that would either integrate with or replace maize. Farmers with 1 TLU (Uel and Oenai) favoured a forage legume-maize relay as it potentially provided both fodder and soil fertility benefits and minimised labour inputs as legumes could be managed at the same time as the maize. This increased income by only 0.1-0.2 M Rp yr^{-1}, which was only 9-13% of the potential maximum economic benefit. Notably, these options only increase whole farm income by 1-3% and, even when bull numbers were doubled, whole farm income only increased by 8-12%. Thus, the economic benefits of a forage legume relay were not the main drivers for potential adoption by these farmers, rather potential increases in soil fertility and reduced labour for cut and carry fodder were the key benefits.

In comparison, at Kesetnana, the participants also favoured a 0.1 ha permanent stand of forage legumes for the economic and labour benefits, with farmers indicating that a permanent stand required less labour than a relay as it was only replanted every five years. However, land constraints meant it had to replace maize. This decreased annual grain production from 0.56 t $year^{-1}$ to 0.45 t $year^{-1}$, costing 0.5 M Rp $year^{-1}$ to replace. This option increased average annual income by 0.2 M Rp $year^{-1}$ but an increase in downside risk resulted in net financial losses of 0.1-1.4 M Rp $year^{-1}$ in three out of ten years. Consequently, land constraints meant that the option selected by Kesetnana farmers increased risk and increased income by only 8% of the maximum achievable financial benefit. Notably, this option increased whole farm income by only 3%, although when bull numbers were also doubled whole farm income increased by 12%.

Table 5.6. Farmers preferences for forage legume management options for six case study farms in West Timor, Indonesia, and the forecast net increase in income from introducing (a) forage legumes or (b) both forage legumes and doubling bull ownership.

Option selected	Area (ha)	Net increase in income (M Rp/yr)		Increase in whole farm income[B] (%)		Increase in household income[B] (%)	
		Legume	*Legume + bulls*	*Legume*	*Legume + bulls*	*Legume*	*Legume + bulls*
Permanent stand on unutilised land							
Camplong	0.40	4.4	6.8	16	26	16	24
Ekateta	0.10	0.8	3.7	5	26	4	17
Manulai	0.10	0.3	2.5	8	68	1	9
Maize-forage legume relay							
Uel	0.20	0.1	1.1	1	8	0.1	2
Oenai	0.04	0.2	0.7	3	12	2	6
Permanent stand replacing maize							
Kesetnana	0.10	0.2[A]	0.8	3	12	1	5

[A] After maize grain purchased
[B] Simulated change in income

5.5. Discussion

Ex-ante whole-farm modelling analysis indicated that integrating forage legumes into crop-livestock systems in West Timor, Indonesia, can increase whole farm income by up to 160%. However, achieving these benefits requires management which maximises financial returns and minimises the impact on staple crop production. Results show that forage legumes are best managed as a permanent stand on uncultivated land, where this is possible, but integration via relay systems is the best alternative where land is constrained. Accounting for the impacts of forage legume substitution for staple grain crops greatly reduces their economic benefit. While bull intensification offers opportunities to further increase income derived from forage legumes, selective feeding will be required to maximise these benefits. While, forage legumes can provide significant financial benefits, participatory modelling indicates that realising these benefits will depend on resource availability – notably labour and land – and farmers' production objectives, as farmers chose options that provided only 8-56% of the potential maximum economic gain that could be achieved.

5.5.1. Forage legume benefits vary with forage legume and livestock management

Forage legumes can provide large production and economic benefits to smallholder farmers through significant increases in livestock production and income. Across the case study farms, introducing 0.4 ha of forage legumes increased cattle turn-off by up to 17-107% (22-157 kg LW/year) and net livestock income by 22-114%. For large cattle herds, this benefit was amplified as forage legume area increased, with 1 ha of forage legumes increasing net livestock income by 46-200% and whole farm income by

27-156%. While these are large economic benefits, forage legume management, herd composition and land availability affect the production and economic gains which can be achieved for different farms.

Management systems that minimise the substitution of staple crops with forage legumes had the largest economic benefits when considered at a whole farm level. Consequently, the most beneficial management options for maize-livestock systems are: 1) where sufficient land and labour resources are available, forage legumes can be permanently established on uncultivated land; 2) when land and/or labour is constrained forage legumes can be integrated into current maize systems using a relay or potentially intercropping or pasture cropping; and 3) intensification of staple crop production could reduce the area required for maize production releasing land for forage legume production. Although previous research in West Timor focused on relays and rotations (Dalgliesh et al. 2010; Nulik et al. 2013), where unutilised land is available permanent stands on uncultivated land offer the largest economic benefit. This is particularly important in West Timor, given <30% of rural households are food secure and thus farmers need to produce food crops on all or most of their arable land (FAO et al. 2010). Yet, there must also be sufficient labour available as farmers with high land:labour ratios may not be able to cultivate additional land with current labour endowments. They may instead prefer to increase labour efficiencies by increasing the productivity of already cultivated land (Komarek et al. 2015). In comparison, maize-forage legume relays commonly offered the largest economic benefit for land constrained farmers. This was because the other two options simulated for land constrained farms – a rotation and a permanent stand replacing food crops – have little or no financial benefit once economic analysis includes the cost of the maize grain replaced by forages. Importantly, while this reduction in staple crop production may be offset by the N benefit of a legume rotation, preferences to allocate legume biomass to livestock production rather than increasing soil fertility means that yield benefits are likely to be small (Chapter 3 and Chapter 4). Other studies have demonstrated that under land constraints relays also provide the opportunity to reduce land competition (Nyambati 2002), increase management flexibility compared to perennial forage options and increase synergies between crop and livestock enterprises (Snapp et al. 1998). While this may increase the land equivalent ratio (LER) (Giller 2001), it remains untested as to whether forage legumes can be integrated into maize intercropping systems, which include intercrops such as cowpea, without reducing either maize or intercrop yield in West Timor. As an alternative to relay cropping, forage legumes could also be managed as an ‘intercrop’ – where they are planted at the same time as staple crops – or as a ‘pasture crop’ – where food crops are planted into a permanent stand of forage legumes. Although these options show promise in other regions (Harris et al. 2007), there can be significant grain and forage yield penalties and thus the potential of these intercrop and pasture crop systems in West Timor requires further research. Finally, while not simulated for this research, intensifying crop production to release land for fodder production is another alternative for intensifying crop-livestock systems. Thus, there are three key options for managing forage legumes to ensure food crop production is not compromised and economic benefits of forage legumes are maximised.

These large economic benefits were driven by the potential of forage legumes to address ‘feed gaps’ – periods when forage supply doesn’t meet livestock demand in terms of quantity or quality (Moore et al. 2009) – and the subsequent increases in cattle reproductive rates and turn-off. The economic impact of using forage legumes to address such feed gaps is determined by the marginal value of feed, which is the rate at which whole farm income increases in response to each additional unit of fodder or megajoule of metabolisable energy (Bell et al. 2008). This study showed that the marginal value of feed was higher for larger herds (>2 TLU; 1.8-3.1 M Rp/t TLU^{-1}) than for small herds (<2 TLU, 0.9-1.0 M Rp/t TLU^{-1}). In part, this was because the baseline diet of smaller herds was higher quality (8-13% legume biomass) than for larger herds (1-7% legume biomass), thus the feed gap for smaller herds was filled more rapidly. When combined with differences in herd size this meant larger herds (>2 TLU) received a greater net economic benefit than smaller herds (<2 TLU) from equivalent areas of forage legumes. Thus, for small herds, farmers may benefit from increasing herd size or focusing on the other benefits such as soil fertility or fodder sales. However, these options may provide little benefit as preferences to use biomass for livestock fodder will decrease soil fertility benefits (Giller et al. 2009) and fodder sales are dependent on a functional fodder market. Despite this, the proportional increase in livestock income from forage legume introduction was independent of herd size and, thus, farmers with small herds may receive meaningful benefits from forage legumes even though the net economic benefit is lower. Consequently, the 35% of farmers in West Timor who own cattle (FAO et al. 2010) are likely to receive economic benefits from forage legume intensification, however farmers with >2 TLU will receive the largest increase in net income.

The marginal value of feed may be increased by preferentially allocating forage legumes to a specific class of livestock and/or feeding forage legumes at certain times of the year when increasing nutrient supply has the largest benefit. Allocating high quality fodder to bulls is likely to increase the marginal value of feed as the market price of bulls in West Timor is 33% higher than for productive cows, with rapidly rising demand for animal products likely to sustain high prices (Herrero et al. 2010; Waldron et al. 2013). Importantly, this is also likely to increase the synergistic relationship between forage legume and bull intensification, a relationship that was limited in current simulations as the model configuration doesn't allow for allocation of different feed types to specific classes of cattle. Alternatively, for cow-calf systems, forage legumes may be allocated to breeding cows to increase reproduction rates or calves could be supplemented with high quality feed to decrease calf mortality, which averages 36% in the region (Jelantik et al. 2008). Given the annual feed gap that occurs in the late wet/early dry season (Chapter 6), it is also important to identify the periods when the marginal value of feed is highest for each of these management options. Thus, further research is required to determine the class of livestock and time of year when targeted feeding of forage legumes has the largest benefit. This is particularly important given investment in technologies, such as improved forages, are often constrained by smallholder farmers' resource endowments – notably land, labour and capacity to invest (Chapter 6; Giller et al. 2011; Ngongo 2011) – indicating farmers may only be able to produce sufficient amounts of biomass to target a small number of cattle for a limited period of time.

Forage legume production varied with agro-climatic conditions, with APSIM simulations indicating that average legume biomass production varied by up to 2.4 t/ha amongst the six simulated farms at different elevations. While these agro-climatic conditions will affect the potential contribution of forage legumes to the feedbase, they will also affect the production of other improved and native forages. While this study focused on herbaceous forage legumes, other perennial forage options may compete with or complement the introduction of forage legumes. To illustrate, dryland farmers in West Timor indicated the tree legume leucaena may be more suitable as, in addition to fodder and soil fertility benefits, leucaena can also be used as a fence or for fire wood (Chapter 6). This demonstrates that legume technologies which provide multiple benefits are more likely to be adopted (Snapp and Silim 2002; Sumberg 2002). However, in land constrained or wetland systems farmers indicated that herbaceous forage legumes or dual purpose legumes were more suitable (Chapter 6). Thus, further analysis is required to determine how the production and economic benefits of a range of forage options differ with resource availability and farming system.

5.5.2. Forage legume intensification risks and constraints

Our study has demonstrated that forage legumes can have a positive impact on financial risk when staple crop production is maintained but a negative impact when staple crop production is reduced. That is, a permanent legume stand on unutilised land or a maize-legume relay increased average net income without increasing downside risk. In comparison, when food crops were replaced with forages, downside risk increased, with financial losses occurring in ≥10% of years. Similar results have been found in western China, with forages incorporated into current food crop systems increasing profit and decreasing risk, while replacing food crops with forages had a negative impact on profit and downside risk (Komarek et al. 2015). Under scenarios when only bull production was intensified without accompanying forage intensification downside risk increased for small (1 TLU) and medium herds (1-2 TLU). However, when both forage legume and bull production were intensified, forage legumes decreased this downside risk for farmers with >2 TLU. This was because small herds had insufficient cash flow to cover the annual cost of purchasing a bull. Consequently, introducing only forage legumes can increase income without increasing risk for a range of herd sizes (1-8 TLU), however when both forage legumes and bull production are intensified only larger herds (> 2 TLU) benefit from both increased income and decreased risk.

While financial and food security risk are important, labour inputs and labour-use efficiency will also affect forage legume adoption. Although we were unable to quantify forage legume labour inputs, participatory analysis showed that labour, rather than land, constrained the area of forage legumes planted, as the majority of case study farmers preferred to planted <40% of the land that was available. In addition, case study farmers also indicated that minimising labour inputs was a key driver in selecting a suitable management option. The issue of labour availability as a constraint to adoption is analysed in more detail in Chapter 6.

5.5.3. Participatory evaluation of simulation outputs

The complex interactions that occur in smallholder crop-livestock systems cannot be fully captured by whole farm models as it is difficult to simulate the link between the economic and socio-cultural factors than define the framework in which a technology is developed and adopted (Cancian 1972; Ojiem et al. 2006; Thornton and Herrero 2001). Participatory modelling can help fill this gap by providing both social and biophysical context to simulation outputs (Sterk 2007). Importantly, this can provide insight into what is feasible by increasing understanding of local production systems and the households managing them (Thornton and Herrero 2001). Thus, this research used participatory modelling to incorporate different farmers' objectives and constraints when determining the most suitable forage legume intensification strategy.

While simulation outputs indicated that a permanent stand provided the largest financial benefit from forage legumes, land availability, labour organisation and production objectives meant some farmers favoured integrating legumes with maize. Livestock focused farmers (>1 TLU) preferred to maximise biomass production by establishing a permanent stand. This also allowed them to minimise labour inputs by only replanting every five years, to use infertile land and to avoid any impact on food crop production. In comparison, crop focused farmers (1 TLU) favoured a maize-forage legume relay as it had the flexibility to provide multiple benefits – fodder and soil fertility – for minimum labour inputs and cost. Notably, no participants selected a rotation, as the labour and input (i.e. herbicide) requirements were higher than a permanent stand despite the lower financial returns for an equivalent area. Thus, even for a small number of households or for groups of men and women, a range of options are required to fit specific socio-ecological niches within smallholder farming systems (Giller et al. 2011).

Although larger areas of forage legumes were more economically favourable, resource constraints – notably labour – meant that case study farmers preferred smaller areas of forage legumes than the model indicated was optimum. The maximum area selected was 0.4 ha, which achieved 56% of the maximum financial benefits of forage legumes for that case study farmer. This equated to a 16% increase in both whole farm and household income. Despite this, areas of 0.1-0.2 ha were more common and, thus, only 5-13% of the maximum financial benefits were achieved. Consequently, for the majority of case studies, farmers selected an option that increased whole farm income by 1-8%. While large economic gains are achievable for some farmers, the impact on land and labour use efficiencies will also determine whether these economic benefits are sufficient incentive for adoption. This is particularly important given increasing pressures on land and labour resources means that improving current resource-use efficiency is critical to improving smallholder livelihoods (Herrero et al. 2010; Waithaka et al. 2006). Thus, the impact on resource-use efficiency, as well as profitability, will drive the potential trajectories for forage legume adoption.

5.5.4. Effectiveness of current analysis

Whole farm models have been developed for integrated farming system analysis, allowing stake holders to explore the consequences of strategic and tactical improvements to farming systems (Groot et al. 2012; Huirne 1990). A range of models have been designed to analyse smallholder crop-livestock systems (Giller et al. 2006; Groot et al. 2012; Herrero et al. 2007; Lisson et al. 2010), providing a variety of tools which differ in scale, complexity, use of a deterministic or stochastic approach, statistical analysis and temporal scale (dynamic vs. static). While models such as IAT (Lisson et al. 2010), FarmDESIGN (Groot et al. 2012) and NUANCES-FARMSIM (Giller et al. 2006) operate at a farm scale, models such as Impact (Herrero et al. 2007) link farm scale system analysis to models assessing policy interventions and regional land use change (Herrero et al. 2005; Herrero et al. 2014). Of these whole farm models, IAT was selected as it allows simulations over multiple years, with seasonal and annual changes in climate, capital and income being carried over to the subsequent year. This dynamic approach, as opposed the static approach applied in FarmDESIGN, enabled evaluation of production variability and risk and provided insight into the frequency which forage legumes improved income and downside risk over a ten-year period. Importantly, IAT does not determine optimal solutions, rather stakeholders and/or researchers are able to assess a range of options in a step-wise fashion, allowing stakeholders to design options which include socioeconomic factors that the model does not account for (Lisson et al. 2010). While IAT was the most suitable option given the research objectives were to assess impacts on whole farm production and household income, other models also simulate environmental impacts, such as erosion and soil N losses (Groot et al. 2012), as well as broader impacts such as regional land use change and economics (Herrero et al. 2014; Sterk 2007). Such modelling would help elucidate the potential impact of forage legumes at a regional level as well as help to develop policies which facilitate intensification of crop-livestock systems.

Changing socioeconomic conditions at a regional or national level will also define farmers ability to intensify or diversify their farming system (Giller et al. 2006) and invest in forage legume production. In West Timor, changes such as decreasing land availability and fragmentation, increasing urbanisation and increasing livestock prices (Ngongo 2011; Waldron et al. 2013), are likely to affect potential trajectories for forage legume adoption. Importantly, at the micro-level, household dynamics and livelihood strategies, especially the distribution of gender roles, are also expected to affect forage intensification and the distribution of benefits (Chapter 6, Quisumbing et al 2014). Understanding how such changes will affect different types of households will help elucidate what kinds of technologies, including forage legumes, may suit different farm types and the social, economic and environmental trade-offs at different scales.

Despite the importance of rice production in West Timor, this study focused on maize-livestock case study farms, as previous forage legume research in the region has focused on these systems, providing a baseline reference for bio-economic modelling (Dalgliesh et al. 2010; Nulik et al. 2013). Yet, there is also potential to introduce a forage legume rotation into rice-livestock systems (Nulik et al. 2013). In rain fed or irrigated systems, this may provide the opportunity to utilise residual soil water and/or to use remaining irrigation water when there isn't enough to produce a second crop. Importantly, assessing a range of crop-livestock systems, rather than focusing on just one key system, could better elucidate the potential adoption and impacts of forage legumes at a regional level.

A common constraint of whole farm models is the difficulty in conducting validation. van Ittersum et al. (2008) argued that, for a component-based modelling approach, validation of model components is appropriate. Previous research has validated the use of APSIM to simulate crop production in West Timor (Hosang 2014) as well as both crop and forage production in a range of smallholder farming systems (Gaydon et al. 2017; Robertson et al. 2005). Livestock simulations relied on model validation by Lisson et al. (2010), which was assessed for bali cattle in eastern Indonesian islands. Lisson et al. (2010) also assessed the socioeconomic model in eastern Indonesia. In addition, crop and forage outputs were also checked against farmers yield records and field experiment data (Dalgliesh et al. 2010; Nulik et al. 2013), and participatory modelling processes also enabled the crop and livestock production predictions to be sensibility tested. Notably, this analysis only analysed forage legume and livestock intensification for 6 case study farms. While these 6 farm types were indicative of key farm types identified in the region (Chapter 6), further analysis of the impacts of forage legume introduction for individual households within each farm type would enable further exploration of the variability for forage legume impacts between both households and farm types.

5.6. Conclusion

This study found that integrating forage legumes into crop-livestock systems can provide large production and economic benefits to smallholder farmers. However, the level of the economic benefit achieved on farm depends on resource availability – notably land and labour – legume management and production preferences. At current prices, management options that maintain staple crop production by integrating forages with food crops or using unutilised land are the only economically viable options. For farm types, livestock focused farmers planned to establish larger areas of forage legumes, indicating farmers with sufficient incentive, land, labour and capacity to invest are likely to receive the largest economic benefit from forage legumes. However, increasing prices for livestock products and competition for resources, such as land, nutrients and biomass, indicate that the scope for forage legume production may expand as farmers face the challenge of feeding more livestock or growing more crops with the same or fewer resources. However, participatory modelling indicates that assessing these adoption trajectories requires extensive farmer input, with improved quantification and disaggregation of labour inputs required to understand the potential social and economic impacts for male and female farmers. At the same time, future research should also consider other improved forages, such as tree legumes, and the complementary opportunities that exist with forage legumes, this will enable researchers and extension officers to identify the range of options that best suit different farm types. Thus, while smallholder farmers can receive significant economic benefits by using forage legumes to intensify crop-livestock systems, these benefits will only be realised if forage legume management is adapted to suit the production objectives and fundamental system properties of a range of farm types.

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We, the Research PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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6. Gender effects on the adoption and impacts of forage legumes in smallholder farming systems

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6.1. Abstract

Herbaceous forage legumes can significantly increase crop and livestock production, however their adoption by smallholder farmers remains low. The low adoption rates are due to a range of agro-climatic, economic, cultural and social conditions – including gender – which define the properties of farming systems and the potential impacts of introducing forage legumes. We examined the benefits and constraints of forage legume production and the comparative value of grain, tree and forage legumes for male and female farmers (n=54) across a range of farm types and agro-climatic conditions in West Timor, Indonesia. Participating farmers grew forage legumes on their farms for two years, over which time a series of separate men's and women's focus groups evaluated forage legume production using a range of participatory methods. Five farm types were identified for participating households using a questionnaire, principal component and cluster analysis, these were then used to further disaggregate results from focus group activities. Results demonstrated that, for women, the key benefits of forage legumes were fodder, soil fertility and labour savings, while men focused more on fodder and increasing livestock production. Although forage legumes could reduce cut and carry labour, labour was the key adoption constraint. Unequal distribution of labour indicated that forage legumes may have a negative impact on women's labour but a neutral or positive impact on men's labour. Comparing legume technologies, concern for food self-sufficiency meant women in food insecure households commonly favoured grain legumes over forages. While men across all farm types favoured fodder production, forage legumes were best suited to land constrained or wetland farming systems and tree legumes to more extensive systems. Therefore, there are a range of opportunities for introducing forage legumes however adoption will require a more equitable distribution of labour and benefits between men and women.

Additional keywords: participatory, farm type, tropical, soil fertility, fodder, labour

6.2. Introduction

The potential beneficial effects of herbaceous forage legumes on crop and livestock production in smallholder farming systems have been widely reported (Ladha et al. 1996; Peoples and Herridge 1990; Vanlauwe and Giller 2006). Yet, adoption of herbaceous forage legumes by smallholder farmers remains low and the potential contributions to soil fertility and fodder remain unrealised (Giller 2001; Sumberg 2002; Thomas and Sumberg 1995). Despite this, an estimated doubling of global meat and milk demand by 2050 combined with increasing pressure for land, water and nutrients and fodder (Herrero et al. 2009), has renewed interest in elucidating the factors driving the poor performance and adoption of forage legumes (Ojiem et al. 2006; Rao et al. 2015; White et al. 2013). In part, the low adoption rates are due to the inability of warm season legumes to consistently provide improvements in soil fertility and animal performance due to high variability in biomass production and N fixation (Bell et al. 2017; Peoples and Herridge 1990). However, there is increasing recognition that, in addition to agro-ecological factors, social, cultural and economic conditions also affect the adoption and impacts of technologies such as forage legumes (Giller et al. 2006; Ojiem et al. 2006).

As the majority of meat and milk produced in developing countries comes from mixed crop-livestock systems (Herrero et al. 2010), there is considerable scope to use improved forages to increase whole farm productivity (Rosegrant et al. 2009). However, it is posited that legume technologies are likely to occupy a niche within smallholder farming systems, rather than acting as a broadly applicable solution to increasing crop and livestock productivity (Elbasha et al. 1999; Ojiem et al. 2006; Sumberg 2002). Ojiem et al. (2006) suggested that the system properties that define the socio-ecological niche for legume technologies include four key factors; agro-ecological, socio-cultural, economic and local ecological conditions. Importantly, legume technologies are commonly adopted when they produce multiple benefits such as food and fodder, reduced labour requirements or weed suppression (Giller 2001; Versteeg et al. 1998). Soil fertility benefits alone are commonly insufficient incentive for forage legume adoption (Franzel et al. 2005; Sumberg 2002). The importance of the benefits differs with gender, with men and women valuing different combinations of benefits for dual purpose and tree legumes (Kiptot et al. 2014; Snapp and Silim 2002). For example, in Malawi, the key benefits of green manured legumes identified by men were soil fertility, water conservation and food security, while for women it was firewood, soil fertility and reduced weed numbers (Snapp and Silim 2002). However, for herbaceous-type forage legumes, very little is known about how men and women perceive the key benefits of forage legumes and how competing preferences affect the identification of a suitable legume technology.

Socially constructed labour and decision making responsibilities for men and women affect adoption of legume technologies and the distribution of benefits (Kiptot et al. 2014; Quisumbing et al. 2014; Snapp and Silim 2002). The diversity of responsibilities and the access to, and control over, resources indicates that gender is also likely to influence the socio-cultural, economic and local agroecological factors which affect the socio-ecological niche for legume technologies. For labour, women are often more constrained as, in addition to productive work, they are also responsible for reproductive and community activities (Moser 1994). Disregard for this distribution of responsibilities often results in new technologies that benefit men more than women, as they reduce men’s labour requirements but increase labour requirements for activities linked to women’s responsibilities such as weeding, harvesting or processing (Quisumbing and Pandolfelli 2009). In addition, women commonly have less access and control over assets, inputs and services, including land, capital, livestock, extension and other productive resources (Quisumbing et al. 2014). While these resource and labour constraints can limit women’s adoption of new technologies, increasing women’s labour requirements can also constrain male innovation activities unless women are able to share the benefits (Doss 1999). Thus, as indicated for tree and grain legumes (Kiptot 2015; Snapp and Silim 2002; White et al. 2013), herbaceous forage legumes are not gender neutral. Consequently, there is a need to understand how gender roles affect adoption potential and the distribution of benefits and constraints of herbaceous forage legume production (Cardey and Garforth 2013; Kiptot et al. 2014; Snapp and Silim 2002).

In this paper, we use a gendered participatory research approach to assess the potential role of forage legumes in crop-livestock systems in West Timor, Indonesia. Although previous research in West Timor quantified the potential crop and livestock production benefits of forage legumes (Dalgliesh et al. 2010; Nulik et al. 2013), the socio-cultural and economic factors governing the use and impact of forage legumes have not been evaluated. Understanding these factors is critical, as there is a large opportunity for smallholder farmers to take advantage of rapidly increasing cattle prices which, in Jakarta, increased 11% per annum from 2002 to 2012 (Waldron et al. 2015). However, defined gender roles and inequalities that exist in the control of and access to resources, information and benefits in West Timor (Oedjoe 2006) mean the preferences and impacts of legume technologies are expected to differ between men and women. Critically, labour inputs differ across farm activities, with women contributing the majority of labour to planting crops, post-harvest processing as well as vegetable and small ruminant production. While men are primarily responsible for large ruminant production (cattle and goats), the migration of men to urban areas to seek off farm employment is increasing women's labour burden (Oedjoe 2006). Combining such gender considerations with a participatory approach to technology evaluation allows researchers to identify whether a technology fits the current farming system, if the resources are available to use it and how the potential impacts may be distributed (Dorward et al. 2003; Quisumbing and Pandolfelli 2009). Importantly, in this case, it also enabled evaluation of the comparative value of different legume technologies (Chikowo et al. 2004; Stür et al. 2002).

Socially constructed gender roles are expected to affect the distribution of the benefits and constraints of forage legume production and their potential role in current farming systems. This paper broadly investigates farmer's own knowledge of their agricultural systems, livelihood needs and the constraints and opportunities that exist for using forage legumes to improve their existing farming systems. To evaluate the comparative value of forage legumes, they were also compared to grain and tree legumes. Thus, this research used the perspectives of male and female farmers from a range of agroclimatic zones and farm types to define the potential socio-ecological niche for herbaceous forage legumes for crop-livestock farms in West Timor. Given the constraints commonly faced by smallholder farmers, it was expected that forage legumes would best suit farmers with sufficient resources and the capacity to use forage legumes to increase household income.

6.3. Methods

6.3.1. Research design

This research investigated the potential benefits and constraints of forage legume adoption and the comparative value of forage, grain and tree legumes for male and female farmers, different farm types and agro-climatic zones. The research involved six case study villages in West Timor, Indonesia, with 6-10 households from each village growing legumes over two years. In each village, gender disaggregated focus groups used participatory activities and semi-structured discussions – which are open conversations guided by a set of informal questions (Grandstaff and Grandstaff 1987) –

to assess farming systems and forage legume impacts. Farm types, determined using a household questionnaire, principal component and cluster analysis, were also used in focus group discussions to evaluate how legume management and technology preference differed with resources and production objectives.

6.3.2. Site and participant selection

Forage legumes butterfly pea (*Clitoria ternatea*) and lablab (*Lablab purpureus*) are well suited to agroclimatic conditions in West Timor (Dalgliesh et al. 2010). Yet, farmers' perceptions of the potential role of forage legumes in crop-livestock systems, and their likely benefits and constraints have not been evaluated. To assess how these perceptions change with gender, farm type and agroclimatic zone, a mixed research methods approach was used to develop a holistic picture of forage legume production, allowing the researcher to investigate 'how' and 'why' questions and to strategically use qualitative and quantitative data to both corroborate and triangulate results (Creswell 2013; Parylo 2012; Yin 2003). Two case study villages were selected at each of three elevations (Lowland 0-300m Above Sea Level (ASL), Midland 300-600m ASL and Highland >600m ASL). One farmer group at each village was then selected to engage in research activities. To maximise the potential benefit and adoption of forage legumes, case study villages and farmer groups were selected on the following criteria: they had high levels of cattle ownership; effective cattle management that prevented crop damage; exhibited fodder constraints, and exhibited higher levels of social capital (the social resources available to pursue livelihood strategies requiring coordinated actions) (Scoones 1998) at the community level.

Case study selection was done in consultation with government researchers and extension officers, village heads and farmer group leaders as well as focus group discussions with farmer group members. Within each farmer group, 6-10 households (n=54) who owned cattle or goats, or were particularly interested in the non-fodder benefits of forage legumes, such as soil fertility or fodder sales, participated in the research activities described below. All households were male headed, thus female participants were from male headed households.

Clear differences in elevation, topography and soil types as well as differences in staple crops (maize or rice), cash crop and livestock production existed between the six case study villages (Dalgliesh et al. 2012; Dalgliesh et al. 2010; FAO et al. 2010; Hosang 2014; Ngongo 2011). Maize, which is the staple crop in midland and highland regions, is grown between December and April. It is commonly intercropped with grain legumes and vegetables, with no fertiliser, manure, herbicides or insecticides applied. In comparison, rice is grown in lowland regions as a mono-crop between November and June, depending on whether it is irrigated; fertiliser and pesticides are applied. After maize or rice are harvested, land is left as a weedy fallow for four to seven months until the following wet season. Differences in wet season duration and rainfall existed between highland (1,465 mm/year) and midland and lowland sites (1,308 mm/year). However, a lack of meteorological stations meant climate data were not available for each site (Table 6.1, see Chapters 4 for more details).

Table 6.1. Key characteristic of farming systems for six sites in West Timor, Indonesia, where farmers tested forage legume production on-farm (Dalgliesh et al. 2012; Dalgliesh et al. 2010; FAO et al. 2010; Hosang 2014; Ngongo 2011).

Classification	Village	Elevation (m ASL)	Landscape	Soil type[A]	Soil organic C[A]	Wetland (ha)	Dryland (ha)	Staple crop	Cattle owned (median, range)
Lowland	Uel	17	Flat, slopes <3%	Inceptosol	1.31	0-1.5	0-2	Rice	1 (0-4)
	Manulai[B]	260	Flat-gently undulating, slopes <5%	Vertosol	2.17	0.2-1	0-1	Rice	5 (0-10)
Midland	Ekateta	422	Strongly undulating slops <45%	Shallow Alfisol	2.83	0	0.9-0.9	Maize	2 (0-4)
	Camplong[C]	437	Gently undulating, slops 5-25%	Alfisol, Inceptosol	1.55	0-0.5	0.2-5	Maize	5 (1-18)
Mighland	Kesetnana	771	Gently undulating slopes 5-30%	Vertosol	2.09	0	0.07-1.3	Maize	1 (0-12)
	Oenai	732	Strongly undulating, slopes <45%	Alfisol	0.28	0-0.2	0.03-2	Maize	2 (1-12)

[A] See Chapter 4 for more details
[B] Manulai No. 1
[C] Camplong No. 2

6.3.3. Characterisation of farm types

Preliminary key informant interviews and focus group discussions revealed there were common farming systems, levels of resource availability and production objectives that existed for the six case studies. To assist in identifying the potential niche for forage legumes, key farm types were identified and then used to assess the integration of forage legumes into crop-livestock systems as well as the comparative value of different legume technologies. To characterise representative farm types, a short questionnaire captured key biophysical and socio-economic structures and crop and livestock practices for each household (n=54). This was validated against locally available crop and cattle production data, with results representing the 25-35% of farmers who own cattle in the Kupang and South Central Timor (TTS) districts (Djoeroemana et al. 2007; FAO et al. 2010; Ngongo 2011). Households were then grouped into five clusters using principal component analysis (PCA) and subsequent cluster analysis (CA) in R (version 3.2.4) using the approach previously described by Tittonell et al. (2010), Bidogeza et al. (2009) and Hair et al. (2010). In total, eight indicator variables were included in PCA, with the five principal components (wetland owned, dryland owned, cattle owned, household members, household labour) with eigenvalues >1 retained for analysis, explaining 76% of the variability of the farms. Hierarchical clustering was then done using the Ward method to separate farms into five clusters. Where households lay in fuzzy areas, they were reclassified by individually examining all factors and making a decision on which group they were best suited to (Tittonell et al. 2010).

The principal component and cluster analysis identified five key farm types (Table 6.2). Two clusters consisted of households which focused on crop production and had low levels of cattle ownership (≤1). Of these two clusters, 'Dryland low LLR' households had a low land-labour ratio (LLR), experienced food insecurity and were most commonly identified at Kesetnana (n=6) and Ekateta (n=6). The LLR ratio is the hectares of land per working family member (age 16-65 years). 'Dryland subsistence' households had a high LLR and were food secure and were most common in highland villages Kesetnana (n=2) and Oenai (n=2). The other three clusters were livestock focused households which had ≥3 cattle, ≥0.6 ha of land and a moderate LLR. Of these clusters, 'dryland and wetland' households cropped both dryland and wetland and were always food secure, these farm types were mainly identified at low land villages Manulai 1 (n=6) and Uel (n=3). 'Dryland only' households only cropped dryland areas and were food secure in most years, with these farm types commonly found at midland villages Ekateta (n=3) and Camplong 2 (n=3) and highland village Oenai (n=5). 'Wetland only' households only cropped irrigated or dryland rice and experienced some food insecurity, and this farm type was only found in lowland villages.

Table 6.2. Characteristics of five farm types identified from a household survery in West Timor and subsequent principal component and cluster analysis. (Median values are presented, the range is presented in parenthesis).

	House-holds (n)	Dryland owned (ha)	Wetland owned (ha)	Maize (ha)	Rice (ha)	Cattle owned (total)	House-hold members (total)	LLR (Land:labour ratio)[A]	Food security
Crop focused									
Dryland low LLR	12	0.1 (0.1-0.8)	0 (0)	0.4 (0.1-0.6)	0 (0)	1 (0-3)	4 (2-8)	0.1 (0.1-0.4)	Sometimes[B]
Dryland subsistence	7	1.3 (0.9-2.0)	0 (0)	1.3 (0.4-2.3)	0 (0-0.3)	1 (0-2)	5 (4-10)	0.4 (0.2-0.6)	Always
Livestock focused									
Dryland only	14	0.6 (0.1-1.0)	0 (0)	0.6 (0.1-1.0)	0 (0-0.3)	4 (3-7)	5 (3-7)	0.3 (0.1-0.4)	Nearly always[C]
Dry & wetland	14	0.2 (0.1-1.0)	0.4 (0.2-1.0)	0.2 (0.1-1.3)	0.4 (0-1.5)	4 (1-9)	6 (3-11)	0.2 (0.1-0.5)	Always
Wetland	7	0 (0)	1 (0.2-1.5)	0 (0)	1 (0.2-2.0)	3 (1-10)	6 (3-8)	0.3 (0.1-0.7)	Sometimes

[A] Land:labour ratio; hectares of land per adults working on the area of land available; [B] Food secure in ≤50% of years; [C] Food secure in 50-90% of years

6.3.4. Characterising crop and livestock production

Prior to planting legumes, a seasonal calendar was developed to evaluate seasonal patterns of on-farm crop and livestock activities and how important problems and resources change over the year (Chambers 1994; Horne and Stur 2003). Seasonal calendars were constructed at each village by a focus group with both male and female participants; with 11-21 participants in each group (Pretty et al. 1995). To start the seasonal calendar, a matrix was drawn on a large piece of paper with numerical representation of months across the top, and key categories each being allocated a row. Participants were first asked to describe their rainfall distribution using a 0-10 scale, with 10 representing the wettest month/s and 0 representing months with no rainfall. Following this, key crop activities and livestock management practices were recorded for the allocated month. Fodder availability was assessed by participants using a 1-10 scale, with 10 representing the highest level of available fodder and 1 the lowest level; and seasonal changes in cattle liveweight were also described.

After constructing a seasonal calendar, the same focus groups then completed a causal diagram to identify linkages between key problems contributing to poor livestock production, strategies farmers use to cope with these problems, and potential intervention points (Dorward et al. 2007; Horne and Stur 2003). After facilitated discussion, the key problems of poor body condition or weight loss during the dry season were identified by participants. This key problem was then written on a card and placed in the middle of a large piece of paper which was divided in two, the top half representing causes and the bottom half representing effects. Participants were then asked to identify the causes of this problem. Each cause was written on a card by the facilitator and placed on the top half of the paper with an arrow indicating linkages between causes and the key problem. Participants then identified the effects of the key problem; they were written on a card and placed on the bottom half of the paper with arrows showing the link between the problem and effects. Current and potential mitigation strategies were then identified for each constraint.

6.3.5. Participatory legume evaluation

Participating households grew forage legumes on their farm for two years (2014-2015). Participants selected between growing either butterfly pea (*Clitoria ternatea*) or lablab (*Lablab purpureus*), which research shows are species suited to local agro-climatic conditions (Dalgliesh et al. 2010). As participants had no previous experience growing forage legumes, technical staff facilitated farmers to determine the area to plant on their farm (0.02 – 0.5 ha), their production objectives –fodder production, seed or soil fertility – and legume management strategy. Notably, all participating farmers chose to use forage legumes primarily for livestock fodder, thus legume biomass was predominantly removed from fields rather than being retained as was assessed in Chapters 2, 3 and 4.

6.3.5.1. Weighted scoring of the benefits and constraints of forage legumes

After the first and second year growing forage legumes, farmers at each village participated in separate men's and women's focus groups discussions, with 6-10 participants per focus group. The benefits and constraints of adopting forage legumes were evaluated using a modified ten seed technique (Jayakaran 2002). Focus group participants first nominated and provided examples of what they considered were the key benefits of forage legumes; with groups identifying between four and seven factors. The number of factors identified was multiplied by five and participants were each given the corresponding number of “counters” (seeds). The key benefits were listed on a large piece of paper, with similar factors grouped to represent one main benefit. Participants then allocated counters to factors according to importance, with more important factors allocated a higher number of counters. If a factor was not considered important then no counters were allocated. Following the scoring, as a group, participants explained why the two most heavily weighted factors were considered to be the most important.

The activity was then repeated for the constraints to forage legume production. Participants listed and provided examples of the constraints or challenges of forage legume production, and then weighted them based on the importance of each constraint in preventing successful integration of forage legumes into their farming system. As described above, participants explained why the two most heavily weighted factors were considered to be the most important factors.

6.3.5.2. Legume management preferences

After the second growing season, the separate men’s and women’s focus groups, with the same participants as the other focus group discussions, also assessed legume management options. The management factors assessed were planting configuration – maize-forage legume relay, sole crop or planted with other forages – and the planting location, which included house land (area surrounding the house), farm land (land where crops are currently planted), uncultivated land (separate to farm land and currently not used for crop production), wetland (used for rice production), and borrowed land (land belonging to other farmers or government, may be free or incur a cost). Using five different coloured markers to represent the five farm types characterised using PCA and CA, each participant was given a coloured marker that represented their farm type. They then placed this marker next to their preferred planting configuration and location, and discussed whether they would prefer to manage forage legumes as an annual or perennial stand. After this, each focus group described how labour and decision making responsibilities for crop and livestock production were divided between men and women, and whether a similar pattern occurred for forage legume production.

6.3.6. Comparing forage, grain and tree legumes

Given the constraints that were identified for forage legume production, and the range of production objectives that exist, the value of forage legumes, grain and tree legumes were compared for the five farm types. Forage legume butterfly pea, which farmers considered the most suitable species, was compared to cowpea (*Vigna unguiculata*) and leucaena (*Leucaena leucocephala*), which are important grain and tree legumes in West Timor (Ngongo 2011; Piggin 2007). For each focus group all participants, regardless of their farm type, assessed whether focusing on increasing production of forage legumes, cowpea or leucaena was the most suitable option for each farm type represented at their village. Participants first discussed the constraints faced by each farm type, and the advantages and disadvantages of each legume option. They then allocated a marker to the legume option which they considered most suitable for each farm type, and explained the potential impact of that legume technology on labour, food security, costs, income and risk.

6.4. Results

6.4.1. Labour and decision making responsibilities

Disaggregation of labour and decision making responsibilities between men and women were similar between all villages. For crop production, men were the main source of labour for land clearing, and also contributed to planting and weeding. In comparison, women were the main source of labour for planting, harvest and post-harvest processing, while also contributing to land clearing and weeding. Children were an important source of labour for planting and weeding crops. For livestock production, men predominantly collect fodder, while men and women share the responsibility for collecting drinking water. For forage legume production, participants indicated that division of labour for land clearing, planting, weeding and seed harvest would be similar to other crops. However, both men and women suggested that forage legumes could increase women's ability to help men collect fodder. This was because forage legumes were considered easy for women to collect as, firstly, they required less physical exertion than tree legumes and, thus, suited women's physical capabilities and, secondly, they could be planted close to the house where women spend a lot of their time working. Consequently, participants indicated that forage legumes could potentially increasing women's contribution to cut and carry labour.

Across the six villages division of decision making responsibilities were similar. Men were commonly responsible for farm land, making decisions about land use and crop management. In comparison, women were responsible for crops grown in the house yard, although women indicated that men often still controlled how the house yard was used. Men made livestock management decisions and interacted with traders, however women commonly controlled cattle marketing including when cattle should be sold and the selling price. Women also commonly controlled household finances. For forage legumes, participants indicated that men were responsible for forage legumes if they were used for fodder, while women were more likely to make decisions around seed production and soil fertility. Although this disaggregation of labour and decision making represent common trends, there was large variation between households depending on household composition.

6.4.2. Characterising livestock production

Fodder availability followed a similar pattern at all villages, with severe feed shortages generally between September and December (Table 6.3). However, the severity of feed shortages varied between villages as the scale (1-10) representing fodder availability was determined by the focus group participants at each village and, thus, the quantity of fodder available for each sale increment differed between focus groups. This variation is demonstrated by the annual fluctuations in cattle live weight. At highland villages cattle gained weight and then maintained it for seven months of the year. In contrast, cattle at midland village Camplong gained weight and maintained it for only five months of the year, losing weight for the other seven months.

Table 6.3. Rainfall, fodder availability and cattle liveweight changes as described by farmers in West Timor, where 10 is the maximum rainfall or fodder available and 1 is the minimum rainfall or fodder available on an annual cycle[A].

Month	J	F	M	A	M	J	J	A	S	O	N	D
Rainfall												
Oenai	8	10	7	8	4	3	2	1				9
Kesetnana	7	10	10	5	3	1	1					6
Ekateta	8	10	9	6	4						2	7
Camplong	10	10	4	1							1	9
Uel	8	10	5	3	2	2				2	3	5
Fodder availability												
Oenai	2	10	10	10	10	10	9	8	4	1	1	1
Kesetnana	6	10	10	9	8	7	5	3	3	3	2	4
Ekateta	8	9	10	10	10	10	8	6	3	1	1	1
Camplong	10	10	10	10	9	7	5	3	2	2	2	6
Uel	10	10	10	10	10	7	5	3	1	1	1	1
Liveweight changes												
Oenai	Gain weight					Fattest		Lose		Skinniest		
Kesetnana	Gain weight				Fattest			Lose weight			Skinny	
Ekateta	Gain weight				Fat	Lose weight			Skinniest		Gain	
Camplong	Gain weight			Fat	Lose weight					Skinny	Gain	
Uel	Gain weight				Fat	Lose weight			Skinniest			

[A]This activity was not completed at Manulai, but is expected to follow a similar pattern to Uel, given similarities in soil, climate and crop production

Cattle management was affected by seasonal conditions, labour, grazing land availability and production objectives. The most common management option was mobile tethering of cows and calves in the late wet season and early dry season, and then permanently tethering and hand feeding them when there was insufficient feed available; this occurred at Oenai, Ekateta, Manulai and Camplong. Free grazing all year was used for larger herds or cows and calves at Camplong and Uel, while low land availability at Kesetnana meant cattle were permanently tethered. Bulls were commonly permanently tethered or managed in a feedlot. The seasonal variation in fodder availability drove labour inputs. During the late wet and early dry season, farmers were either not collecting fodder for their cattle or, if they were, they were only spending one hour collecting it. In comparison, in the late dry and early wet season (August-December) farmers were spending up to four hours a day collecting fodder.

Key constraints to livestock production identified in causal diagrams indicated that the most common causes of poor growth or weight loss were related to forage quality and availability, as well as disease and insufficient drinking and irrigation water to grow forages. Importantly, fodder constraints were driven by declining forage quality in the dry season, free grazing livestock, land availability, and not knowing how to conserve excess fodder as hay. The consequential weight loss resulted in poor reproduction rates, mortality and low sale prices. While the causal diagram focused on factors affecting weight gain, cattle theft was considered a serious problem at Manulai, Camplong and Ekateta, with some farmers preferring not to increase cattle production because of the risk of theft.

6.4.3. Production and economic benefits of forage legumes

Across the two growing seasons, farmers at all villages said that forage legumes were highly productive, indicating they grew well under local agro-climatic dryland conditions. Butterfly pea was favoured by participants at all six sites, as the perennial growth habit meant that butterfly pea planted in February 2014 was still producing biomass during the 2015 dry season, with farmers continuing to collect biomass through to the middle of the dry season (August). In addition to high biomass production, farmers also harvested large amounts of seed from small areas, with seed yields >1 t/ha reported.

Participants ranked the key benefit of forage legumes as increased availability of high quality fodder (Figure 6.1), with fodder benefits the only factor identified as important by all focus groups. Participants indicated that leaf and stem material was highly palatable to cattle, goats, pigs and chickens however, they had not observed increased liveweight as they had produced insufficient legume biomass to sustain weight gains. Increased fodder availability in both the wet and dry seasons was considered important as forage legumes could fill the feed gap in the late dry season, or alleviate labour requirements in the wet season when farmers were busy with food crops. Importantly, men and women consistently stated that they preferred to use forage legumes to fatten bulls rather than feed them to cows and calves or use them as a green manure as they expected higher and more immediate financial returns from bull fattening.

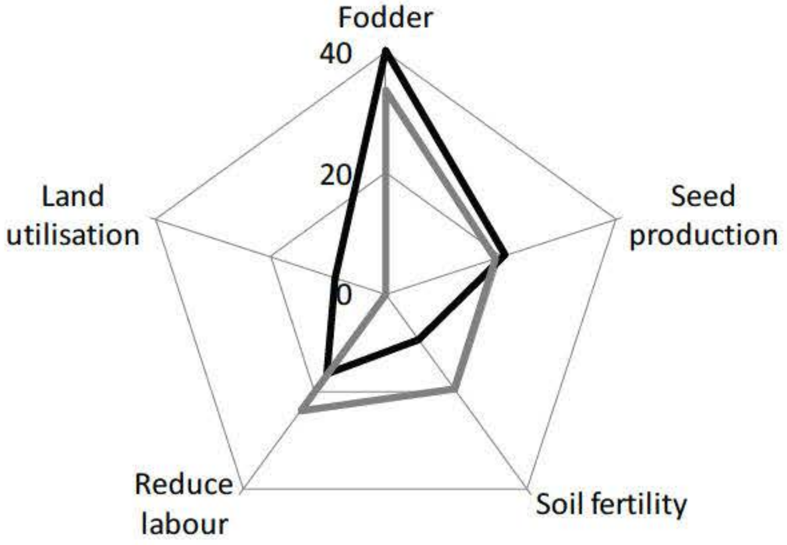


Figure 6.1. Key benefits of forage legumes identified by women (grey) and men (black) at 6 villages after two years growing forage legumes^{A}.

^{A}Axis is the proportion of markers allocated to each factor, not all markers are included in the graph as minor benefits were excluded.

Reduced cut and carry labour requirements and easier fodder collection were also important. Men and women indicated that fodder could be quickly collected, as the forage legumes could be planted close to the house and there was no need to climb trees, as they do for tree legumes such as leucaena. Consequently, participants estimated that forage legumes would reduce cut and carry labour requirements from 4 hours/day to 1 hour/day. Given the ease of harvesting fodder, forage legumes were considered suitable for women, children and elderly people to collect, which is in contrast to tree legumes which are commonly only harvested by able bodied men. Although men and women made similar observations about labour savings, women considered labour savings more important than men, allocating 24% of markers to labour savings compared to only 16%.

Soil fertility, seed production and increased land utilisation were other important benefits. After two years growing forage legumes, soil fertility was more important for women than men, with women allocating 19% of markers compared to 9% for men. Soil fertility benefits included the opportunity for reduced fertiliser costs, increased yields and reduced risk of crop failure. Seed production was considered highly profitable by both men and women as the price of forage legume seed (25,000-50,000 Rp/kg) was higher than the price of other cash crops, such as mungbeans (15,000 Rp/kg). Thus, farmers indicated that seed production offered high returns on labour inputs compared to other cash crops. Finally, some male participants indicated that increased land use efficiency could be achieved by intercropping with maize and replacing weedy fallows with high quality fodder. However, it was observed that such management could compete with land used for traditional women’s crops, such as mungbeans, that are planted after maize harvest.

Comparing between villages, for highland villages, seed production and soil fertility were the key benefits, with these factors allocated ≥30% of markers each compared to labour savings which were allocated ≤15%. Increased land utilisation was also important at highland village Kesetnana, where there was a large number of crop-focused households with low LLR. In comparison, fodder and labour savings were the key benefits at lowland and midland villages, with ≥40% markers allocated to fodder production and ≥15% for labour savings. The key difference between these four lowland and midland villages was that soil fertility and seed production were important secondary benefits at Uel and Ekateta, but not at Manulai and Camplong. These differences were because farmers at Uel and Ekateta had experience selling seed and indicated that, from their perspective, the cost of synthetic fertilisers was too high.

6.4.4. System constraints to forage legume production

Although reduced cut and carry labour was the key benefit of forage legumes (Figure 6.1), labour for land preparation, planting and weeding was the key constraint at all villages, with >35% of markers allocated to labour constraints by each focus group (Figure 6.2). This is because the optimal time for planting legumes occurred when farmers were busy planting and weeding staple crops. Participants indicated that the first opportunity to plant legumes may be near the end of the wet season in February or March, when there are fewer rainfall events and planting opportunities. Participants also said that, compared to maize or king grass, legume management is laborious as the small seeds mean forage legumes are more time consuming to plant and harvest seed, and the slow canopy closure increases weeding requirements. Importantly, women considered these labour constraints more important than men.

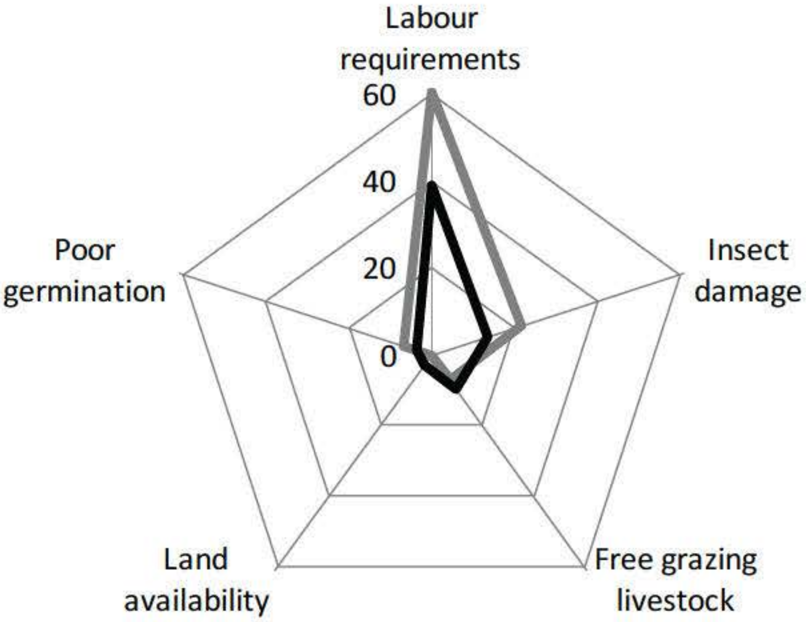


Figure 6.2. Key constraints to adopting forage legumes identified by women (grey) and men (black) at 6 villages after two years growing forage legumes[A].

[A] Axis is the proportion of markers allocated to each factor, not all markers are included in the graph, as minor constraints were excluded.

Free grazing livestock, insect damage and poor germination were also important constraints. Free grazing livestock were a major constraint at all villages except Kesetnana and Uel, where there are village rules that all cattle must be tethered or fenced to prevent crop damage. At the other four villages, neighboring farmers' cattle, goats and pigs ate the legumes regardless of whether the legumes were fenced or not, as fences were often poor quality, or were cut by other farmers. Legumes planted near the house to prevent theft were often damaged by chickens. Insect damage to butterfly pea and lablab reduced legume biomass and seed production across all elevations, with participants at the four villages affected allocating ≥20% of markers to insect damage. While insect damage was a problem across all elevations, the highest levels of damage (80% defoliation) was reported at Uel. Importantly, farmers either did not know how to reduce insect damage or didn't have the resources to source a suitable insecticide. Poor germination was an important constraint in the first growing season due to poor quality seed. In the second growing season poor germination was due to late planting resulting from labour constraints.

A range of other minor constraints were identified including seed supply and the sustainability of the seed market, high seed losses due to shattering, inability of forage legumes to contribute to food security, slow financial returns from fodder production, legumes requiring termination before maize is planted on the same land and limited access to information. Despite this range of constraints, land availability was not a concern, with farmers indicating they either had access to unutilised, farmer group or government land or were able to plant forage legumes with other crops. The exception was at Camplong where alfisol soils were considered unsuitable for forage legume production compared to inceptosol soils, with farmers who only had access to alfisol soils facing land constraints.

6.4.5. Forage legume management

The temporal aspects of forage legume production were consistent across the case study villages, with both men and women preferring to reduce labour requirements by managing forage legumes as a perennial rather than annual forage. However, the spatial dynamics of legume management differed with gender, village and farm type. At all villages, except Eketata, ≥50% of women preferred a maize-forage legume relay over other management options (Figure 6.3). This was driven by soil fertility and crop yield benefits as well as increasing land use efficiency, land availability and lower labour requirements for land preparation and planting. In contrast, at Ekateta, 88% of women preferred a single stand of forage legumes because they were concerned forage legumes may reduce maize or intercrop yield. In comparison, ≥50% of men at all villages, except Uel, preferred to plant forage legumes as a single stand or with tree legumes as they indicated it would result in higher biomass production as well as easier weeding and fodder collection. Notably, planting with leuceana was considered an important option at Camplong and Oenai but not at other villages. At Uel the majority of farmers favoured relay cropping as an option for reducing fertiliser costs. Despite these differences for gender and village, the only consistent difference in legume management preferences between farm types, was that planting with leucaena was only considered suitable for livestock-focused farm types as it enabled farmers to develop land that was allocated solely to fodder production.

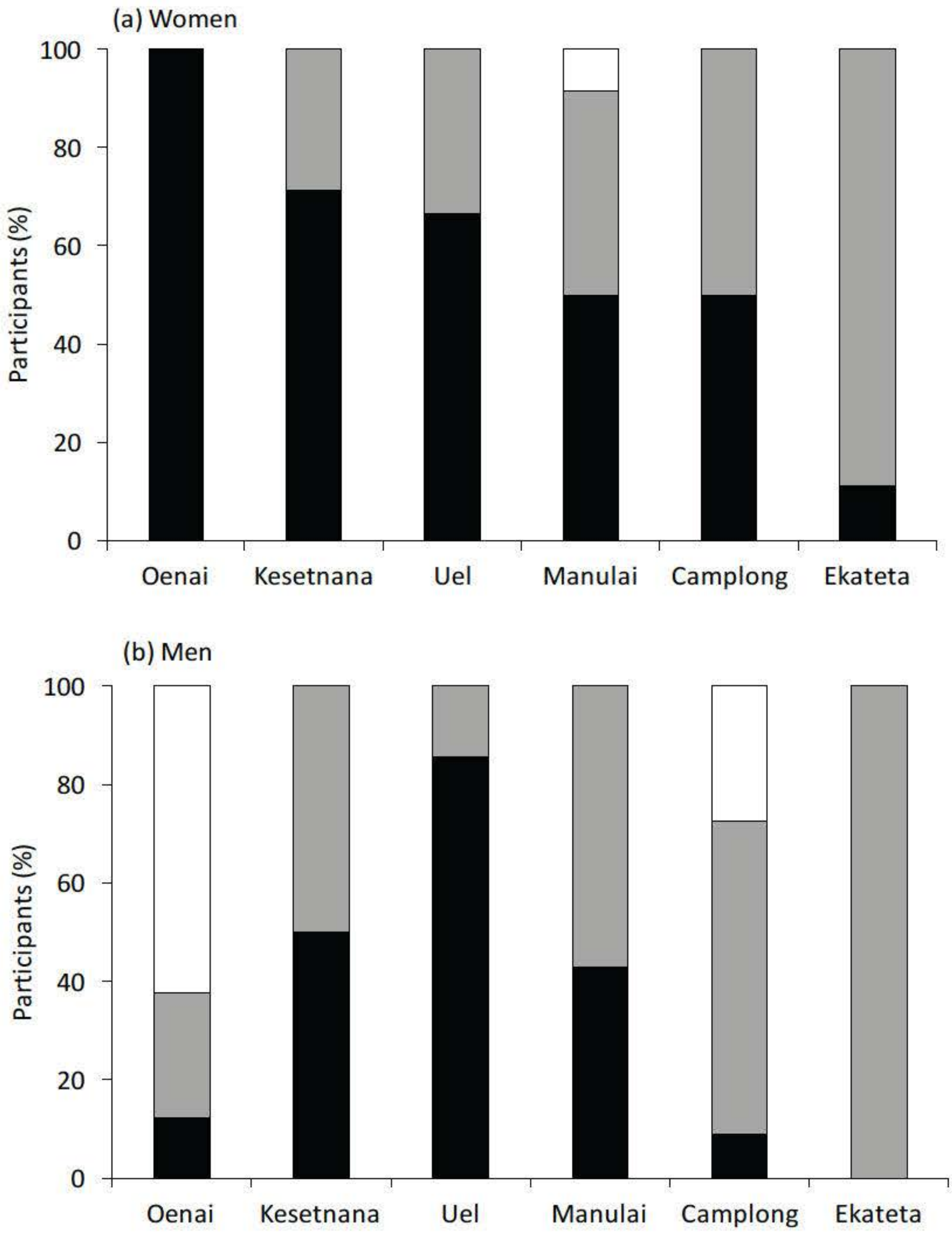


Figure 6.3. The percentage of female (a) and male (b) farmers at six villages in West Timor that favoured managing forage legumes as a maize-forage legume relay (black), as a single stand (grey) or planted with leuceana (white).

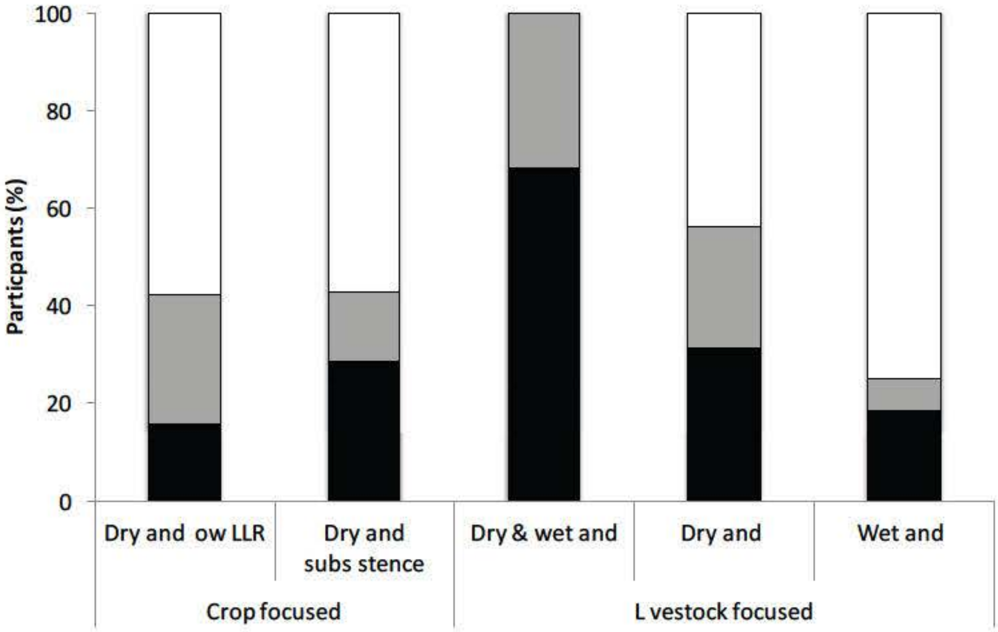
Preferred planting location was driven by land availability and access as well as production objectives. Farm and house land were suitable options for both men and women, however men indicated that they could also plant legumes on uncultivated or borrowed land while women did not. For example, at Camplong 88% of women said they would plant legumes on farm land while 63% of men said they would plant legumes on land borrowed from the government. At Manulai, Kesetnana, and Oenai, farm land was the most suitable option for men and women, with ≥57% participants in each focus group preferring this option. This was driven by the dual soil fertility and fodder benefits, as well as the fact that the land was already fenced and was away from free grazing chickens and pigs. In comparison, at Ekateta, house land was considered most suitable by ≥55% of men and women as planting forages close to livestock reduced labour inputs. At Uel, planting forage legumes on wetland after rice harvest was also considered a suitable option for men and women. Comparing farm types, livestock focused farmers (≥50%) favoured farm land as it allowed them to plant the largest areas of forage legumes while simultaneously increasing soil fertility of crop land. Crop-focused low LLR households also favoured farm land because of the soil fertility benefits. In comparison, 67% of dryland subsistence focused farmers favoured planting legumes close to the house to save on management and cut and carry labour requirements, although the area of forage legumes that could be planted near the house was limited.

6.4.6. Comparative value of forage, grain and tree legumes

Given the constraints identified, alternative legume technologies were also assessed (Figure 6.4). Where households experienced food insecurity, women favoured increasing cowpea production over livestock fodder, allocating ≥44% of markers for cowpeas for food insecure farm types. In addition to increasing food security, women indicated that focusing on cowpea production could also increase fodder availability and soil fertility, while excess grain could be sold. In comparison, for the same farm types, men favoured fodder production, allocating 80-100% of markers to forage legumes and leucaena, suggesting that even if households are food insecure these forages could increase soil fertility, or that cattle could be sold to meet household food requirements.

While both forage legumes and leuceana were considered high quality fodder, there were distinct advantages and disadvantages for each fodder. The perceived advantages of forage legumes were the potential to increase soil fertility and crop yield, easy forage collection, ability to intercrop and reduce land requirements, rapid biomass and seed production, and ability to plant it in wetland areas. However, compared to leucaena, it produced less biomass and required significantly more labour to weed, as once leucaena is established no further weeding is required. The other perceived advantages of leucaena compared to forage legumes were the option to plant it along a fence line to minimise land requirements, to improve fence strength, as a source of fire wood and once established it is too tall to be grazed by cattle. Given these advantages, men favoured leucaena over forage legumes when suitable dryland was available.

(a) Women



(b) Men

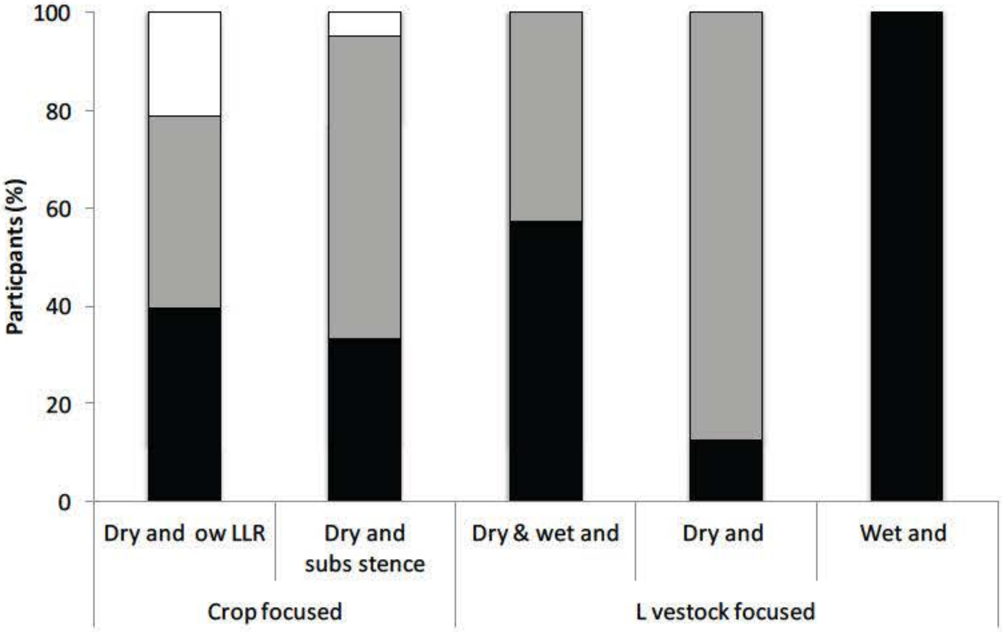


Figure 6.4. The most suitable legume technology – forage legumes (black), tree legumes (grey) and grain legumes (white) – for five different farm types according to farmers from six villages in West Timor[A].

[A] According to 56 female and 45 male participants from six villages, participants across all farm types voted for which technology was suited for each different farm type.

6.5. Discussion

This paper reports that the benefits and constraints of forage legume production differ for male and female smallholder farmers. While smallholder farmers identified a range of key benefits such as fodder production and soil fertility, both male and female participants indicated that the labour required for forage legume production was unequally distributed, indicating that forage legumes may increase women's labour requirements while maintaining or decreasing men's labour inputs. From the farmers' perspective, food secure households who are fattening bulls are the most likely beneficiaries of forage legume production, indicating that, currently, potential adoption of forage legumes in West Timor, Indonesia, is limited to the <35% of farmers that own cattle (FAO et al. 2010). The impact of forage legume production on male and female smallholder farmers, the benefits and constraints experienced across a range of agro-climatic zones and farming systems and the comparative value of a range of legume technologies are discussed below.

6.5.1. Forage legumes benefits and constraints vary with gender

N_2 fixing legumes have been successfully adopted when the technology produced multiple benefits such as fodder and food, reduced labour and weed suppression (Chikowo et al. 2004; Giller 2001; Kiptot et al. 2014). Forage legumes can also produce multiple benefits however, the value of these benefits varies between men and women. Women identified fodder production, reduced cut and carry labour, and improved soil fertility as the key benefits, while men indicated production of high quality fodder and the subsequent fattening of bulls as most important. This reflects women's concern for domestic and reproductive work, household finances, and the provision of household food, and men's responsibility for cattle husbandry (Moser 1994; Oedjoe 2006; Quisumbing and Pandolfelli 2009). While seed production was also considered important, seed sales are unlikely to remain important beyond the completion of the project until a formal seed market is established in West Timor. Notably, male and female participants consistently favoured using legume biomass to fatten bulls, rather than for raising calves, seed production or increasing soil fertility. This is driven by the economic value of cattle, their role as an investment and risk management strategy (Ngongo 2011), as well as government policy which stipulates that unproductive cows may not be slaughtered, and that only bulls >250 kg liveweight may be exported to islands outside the province (Waldron et al. 2013). This preference for fodder over green manuring reflects findings from sub-Saharan Africa, where crop stover and mulching materials are preferentially fed to livestock rather than being retained to improve soil fertility (Giller et al. 2009). Importantly, these results are limited to male-headed households as female headed households (which were not included in this study) experience a larger number of constraints, such as access and control over resources, that are likely to affect potential forage legume adoption (Doss 1999). Hence, for male-headed households, high quality fodder is the key benefit of forage legume production, however the importance of this and other benefits differs with gender.

While reduced cut and carry labour was a key benefit, labour inputs were also the key constraint to adoption. Farmers indicated that forage legumes could reduce cut and carry labour by three hours per day but, at the same time, they increased labour inputs at times of peak labour demand. This is because the optimal time for establishing forage legumes (December-February) is when farmers are busy with staple crops.

Consequently, participants indicated that the earliest opportunity for planting forage legumes would be near the end of the wet season, when the risk of poor establishment is high. To reduce these labour inputs, farmers favoured establishing a permanent stand, as it only required replanting every five years (Pengelly and Conway 2000). Critically, the distribution of labour savings and inputs are likely to be unevenly distributed between household members. For women, total labour inputs are likely to be more acute given current labour constraints (Oedjoe 2006), their responsibility for planting and weeding and their potential increased contribution to cut and carry labour. In comparison, men's labour requirements may decrease given their responsibility for fodder collection. Thus, if there is not a reallocation of these roles between men and women or development of labour saving technologies, there will be a low adoption of the technology or an increase in women's labour burden (Doss 1999).

Despite decreasing land availability and increasing fragmentation in West Timor (Ngongo 2011), land was not an important constraint. Consequently, if large communal grazing areas still exist farmers are unlikely to allocate resources or labour to tethering cattle and feeding cut and carry fodder (Kana Hau et al. 2014). Despite this, some farmers indicated that forage legumes provide the opportunity to increase land productivity. This potential increase in resource-use efficiency demonstrates that forage legumes can contribute to the synergies between crop and livestock husbandry such as increased soil fertility and stover production (Thornton and Herrero 2015). However, the level of integration between forage and crop production differed with gender. In this study, female farmers commonly favoured a higher level of integration, preferring to plant maize-forage legume relays because of the potential dual soil fertility and fodder benefits, despite possible negative effects on intercrops. In comparison, male farmers favoured lower levels of integration, preferring a single stand of forage legumes because of higher biomass production. Although manure application can also be an important synergistic benefit of forage technologies (Stür et al. 2002), cattle in West Timor are often fattened in areas that are separate from the farm (Ngongo 2011) and, consequently, the labour requirements for the collection, transport and application of manure commonly prohibits its use as a soil fertility amendment strategy (Bayu et al. 2005; Ngongo 2011). Therefore, despite crop-livestock synergies contributing to sustainable increases in farm production (Herrero et al. 2010), forage legumes do not consistently increase the synergies between crop and livestock management, rather these synergies vary with the production priorities of male and female farmers.

6.5.2. Forage legume benefits and constraints vary with farming system and agroclimatic zone

While fodder production was an important benefit for both men and women, its importance differed across elevations, as it was more important in regions with lower rainfall (midland and lowland) than those with higher annual rainfall (highland, Chapter 4). This reflects differences in fodder availability and liveweight gain, with cattle losing weight for 5 months/year in highland regions compared to 6-7 months/year in midland and lowland regions (Table 6.3 and Chapter 5). Importantly, soil fertility was a key benefit at highland villages, but only considered a secondary benefit at midland and lowland villages that experienced low maize production. This reflects the low maize yields at highland villages (Chapter 4). Thus, the importance of soil fertility and fodder production also vary with agro-climatic conditions and crop management.

In addition to labour constraints faced by male and female farmers, local customs and laws, as well as biotic and abiotic constraints also affected forage legume production. Crop damage by livestock was a problem where there were free grazing livestock or insufficient rules and penalties governing livestock management. This indicates that forage legumes are likely to be more successful where damage can be prevented by enforcing rules for free grazing livestock (Ngongo 2011). Such collective action for management of free grazing livestock is commonly most beneficial and effective in areas with high social capital (Gebremedhin et al. 2004), indicating forage technologies are more likely to be successful for a community with high levels of trust and cooperation. Therefore, social capital within a farmer group and community will affect the successful adoption of forage legumes.

Insects were also a significant problem across all elevations, with high levels of defoliation and damage to seed pods. While farmers prefer butterfly pea because of its perennial growth habit, of the species which perform well in West Timor, it is the most susceptible to insect damage (Nulik et al. 2013). Nulik et al. (2013) suggest that insect damage can be minimised by harvesting biomass once low levels of insects are present. However, unless farmers are able to conserve this biomass as hay, the fodder cannot be used over an extended period to maintain or increase livestock production as it is likely to degrade. Therefore, managing insect damage on-farm needs further research and extension efforts to ensure the benefits of forage legumes are realised.

6.5.3. The comparative value of forage, grain and tree legumes differ with gender

This research demonstrated that the adoption of forage legumes is largely constrained by labour, free grazing livestock and production objectives. Research in sub-Saharan Africa indicates that grain and tree legumes can deliver similar benefits to forage legumes, while potentially addressing some of these constraints (Chikowo et al. 2004; Giller 2001; Kiptot et al. 2014). Key findings indicate that, for the majority of farmers, grain (cowpeas) or tree legumes (leucaena) were favoured over forage legumes (Figure 6.4). Preferences for legume technologies reflected both production objectives and the household responsibilities of men and women. For households that experienced some level of food insecurity, women commonly favoured increasing cowpea production over forage legumes or leucaena, indicating that cowpeas had the potential triple benefit of increasing food security, soil fertility and fodder availability, as well as household income where excess grain was produced. This reflects the inability of poorer farmers, especially women, to self-insure against shocks and maintain food security through cashing in nonproductive assets (Barrett et al. 2001; Gladwin et al. 2001). This indicates that unless a legume technology produces grain for household consumption, women in food insecure households are unlikely to adopt it.

In comparison, even when households were food insecure, men favoured forage technologies over grain legumes. However, preferences for leucaena or forage legumes differed between farm types. Forage legumes were best suited to wetland systems as they could be managed as an annual rotation, with participants indicating that tree legumes would reduce rice yield, with farmers on the island of Lombok experiencing similar problems with tree legume *Sesbania grandiflora* (Kana Hau et al. 2014). Where only dryland was available, leucaena was commonly preferred as the men indicated that, in addition to being a high quality feed, it could also act as a fence, provide firewood and increase soil fertility if required. However, if land availability was limited, the men indicated that forage legumes may be preferable as planting leucaena in close proximity to food crops could reduce crop yields. Despite this, Kana Hau et al. (2014) found that, with the exception of the Amarasi region, the adoption of leucaena in West Timor has been slow. In part, this is attributed to concerns about free grazing livestock damaging newly established plots, an increased risk of theft when cattle are tethered rather than grazed on communal land, and insufficient labour or motivation to establish forages when communal grazing land is available (Kana Hau et al. 2014). While the availability of communal land is currently a disincentive for establishing improved forages, decreasing land availability and fragmentation (Ngongo 2011) and increasing demand for beef in Indonesia (Waldron et al. 2013) may increase the value of improved forages.

6.5.4. Socio-economic niche for forage legumes

Forage legumes suit a range of local agro-ecological conditions in West Timor, however there are socio-cultural and economic factors which define their potential niche in crop-livestock systems. Management and production preferences indicate that, compared to other legume technologies, forage legumes are best suited to food secure farmers with large herds of cattle (≥3 cattle). However, in West Timor, <35% of farmers own cattle and even less are fattening bulls – farmers prefer to feed legume fodder to bulls – indicating that the current scope for adoption is quite small (FAO et al. 2010; Waldron et al. 2013). Given the small number of farmers involved in this research, further validation of this potential socio-economic niche would require a larger sample size to capture the heterogeneity within and between sites. Despite this small sample size, low levels of food security (<30% of households, FAO et al. (2010)) and acute labour shortages (Djoeroemana et al. 2007) mean that, for the majority of households, the comparative value of forage legumes will be significantly lower than grain or tree legumes. In such circumstances, multipurpose varieties of cowpea, which produce large amounts of biomass and grain, may be a suitable option (Giller 2001; Sanginga et al. 2001). This reflects findings in Africa where farmers prefer to use other technologies, such as tree legumes or synthetic fertilisers, to increase farm production (Giller et al. 2009). Thus, current farmer perceptions indicate that the key socio-ecological niche for forage legumes are households which receive income from fattening bulls, are food secure and distribute labour so that forage legumes either maintain or decrease labour requirements for both men and women.

Despite the small socio-ecological niche that currently exists for forage legumes, further research and development as well as market and policy changes may shift how farmers perceive forage legumes, and provide opportunities to modify or mitigate production constraints as well as amplify the benefits. Development of labour saving technologies for land clearing, planting and weeding are critical, with such options including herbicides, broadcasting rather than dibble planting, and the adoption of vigorous varieties with rapid canopy closure. Perceived socio-ecological niches for forage legumes may also change with further research and development, with three alternative niches identified. Firstly, supplementary feeding forage legumes may reduce the high post-natal calf losses (>30%) in the region (Jelantik et al. 2008). Secondly, provision of high quality fodder during shipping to Java may reduce weight losses during transport and alleviate the requirement for compensatory feeding by importers (Waldron et al. 2013). Thirdly, Eastern Indonesia has suitable agroclimatic conditions for forage legume seed production, providing the opportunity for a more rapid return on investment than cattle production (Nulik et al. 2013). Accordingly, there are a range of niches for forage legumes which may expand in response to further research and development, and market and policy changes.

6.5.5. Value of using gender to evaluate socio-cultural, ecological and economic factors

This study has demonstrated the importance of using gender to assess the socio-cultural and economic conditions that affect the performance of a technology. While previous forage legume research has reported intra-household impacts (Ahmed 2012; Connell et al. 2010; Maxwell et al. 2012), we are not aware of any forage legume studies that assess the impacts across the full production cycle or which link gender aspects to agroclimatic conditions and farm type. In this study, gender disaggregation enabled researchers to identify that, while the net benefit to a household may be positive, the distribution of this benefit was uneven. Importantly, elucidating women's marketing power demonstrated that the potential benefits of forage legumes could be further amplified by improving women's market access. Using a gender lens can also guide future research and develop extension which targets women based on their explicit livelihoods, labour constraints, preferences and assessments of their needs (Chowa et al. 2013; Doss and Morris 2000; Sambodo and Nuthall 2010). Ensuring equal access and control over information is particularly important, given women's adoption of tree legumes and improved fallow technologies has been constrained by access to information and intra-household decision making factors (Kiptot et al. 2014; Mango 2002). Thus, understanding information flows and how this information is used for tactical and strategic decisions around resource allocation and trade-offs is a critical aspect determining the potential for farmers to invest resources in establishing forage legumes (Giller et al. 2006). Thus, specifically targeting women farmers to gain their perspectives and opinions on agricultural systems adds enormous value to research into farming systems, the division of labour and the potential livelihood impacts of new technologies.

6.6. Conclusion

This study found that forage legumes do not have universal utility, rather they are most likely to benefit farmers with large resource endowments that are fattening and trading bulls. However, unequal division of labour and access and control over resources is likely to result in uneven distribution of the benefits and constraints of forage legume production. Consequently, future research should not assume homogeneity or unanimity, rather it should specifically target the key benefits and constraints identified by men and women. For this research, reducing labour inputs for women's activities and maximising the range of primary and secondary benefits identified by men and women across case study sites are most critical. Importantly, future expansion of forage legume use will also require careful targeting of extension activities. Targeting villages with high social capital will increase the likelihood of successful adoption, while gender empowerment and social capital building activities will increase local adaptive research and farmer to farmer learning. This is particularly important given current adoption is constrained by social and human capital rather than natural and physical capital. In addition, such extension activities can also strengthen innovation networks, enhancing the development of alternative niches for forage legume production. Despite the sound agronomic performance of forage legumes in West Timor, the current niche for forage legumes is small, with further evidence of the labour, production and economic benefits required to achieve wider adoption.

6.7. Acknowledgements

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Higher Degree Research Thesis by Publication

University of New England

STATEMENT OF ORIGINALITY

We, the Research PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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7. Discussion

Identifying the potential impacts and adoption trajectories of a new technology requires farming systems research that applies a broad perspective (Norman and Collinson 1985). This includes accounting for the perceptions and priorities of farmers (Chambers 2008) and the sociocultural context in which they operate (Ojiem et al. 2006), as well as the economic feasibility, resource endowments and biophysical elements (Giller et al. 2011; McCown et al. 2012; Ojiem et al. 2006). The most novel aspect of this thesis is the integration of three separate approaches – field experiments, farming systems modelling and participatory socioeconomic analysis – to assess the integration of herbaceous forage legumes into smallholder farming systems. Integrating different research approaches allowed for more robust and contextualised conclusions to be drawn, providing a more holistic insight into the potential role of forage legumes in smallholder farming systems (Giller et al. 2011; Sterk 2007). To illustrate, field experiments underpinned the farming systems model inputs which, in turn, allowed estimates of the potential production and whole farm economic impacts for smallholder farmers. While simulation outputs indicated that large economic gains were achievable, participatory analysis demonstrated that resource constraints and gender relations influence the level of benefits which may be achieved on-farm.

As demonstrated in this thesis, integrating techniques brings value to research when the ‘proof of concept’ for a new technology has been established (Nulik et al. 2013) but the performance of the technology at a farm and household level has not been assessed for a range or farm types, environments or management options. However, the combination of suitable techniques depends on the research question. For example, field experiments are sufficient to determine a range of forage legume species which suit the agro-climatic conditions (Dalgliesh et al. 2008) but farmer participation is required to determine which of these species actually suit local farming systems and production objectives. For this thesis, previous field experiments by Dalgliesh et al (2008; 2010) established that managing forage legume relays and rotations could increase crop or livestock production, yet simulation and participatory research presented in this thesis demonstrated that a permanent stand or relay are more favourable options for smallholder farmers. Thus, the socioeconomic context provided by farming systems modelling and participatory evaluation allows researchers to better understand whole farm and household impacts which can then be used to direct future research and extension programs.

7.1. Fodder removal reduces forage legume soil N and yield benefits

Tropical and subtropical forage legumes can be an important source of N in mixed crop-livestock systems (Herridge et al. 2008; Peoples and Herridge 1990), yet there is little research quantifying the impact of legume biomass management (retain vs. remove) on dry matter production, soil N and subsequent cereal crop yield. Understanding how legume management affects soil N is particularly important for smallholder farming systems as, while farmers often preferentially allocate biomass to livestock production (Giller et al. 2009), declining soil fertility also constrains crop yields (Lal 2004). Thus, understanding the trade-offs between fodder production and increasing soil N are critical to understanding the allocation of N benefits in mixed crop-livestock system. This thesis (Chapters 2-4) quantified both the maximum potential N benefits as well as the N benefits which are likely to be achieved on-farm.

In Chapters 2 and 3, the potential net inputs of fixed N, fertiliser equivalence values and the impact on subsequent maize yield were investigated for an irrigated system to remove interactions with soil moisture and N supply. The field experiment found that when legume shoot biomass was retained, potential net N inputs of 290-540 kg N/ha are achievable, providing equivalent to 100-148 kg urea-N/ha and increasing subsequent crop yield by 6-8 t/ha. Indicating that the maximum N benefit from tropical forage legumes (Chapters 2 and 3) is at least double what is commonly achieved under dryland conditions (Armstrong et al. 1999b; Bell et al. 2017; Peoples and Herridge 1990). In comparison, when shoot biomass is cut and removed for fodder there was little or no impact on soil N and subsequent crop production. Demonstrating that, while sizable N inputs are achievable, there are large trade-offs between allocating legume N to increasing crop or livestock production.

In Chapter 4, simulations assessing the impact of legume biomass management (remove vs. retain) also demonstrated the large trade-offs associated with legume management. Simulations across a range of agro-climatic conditions indicated that the largest and most consistent N yield benefits were achieved for sites and years with low soil N and high crop yield potential. However, high maize sowing densities (≥4 plants/m^2) and effective weed management were required to maximise yield benefits from legume N inputs. Where maize yield potential is lower, only 1-3 t/ha of legume biomass may need to be retained to maximise yield benefits, with the remaining biomass able to be used as fodder. Notably, minimum maize yield didn’t increase in response to legume N, indicating that, in West Timor, water is the key limitation to crop production in poor years. Thus, even when shoot biomass is retained yield benefits aren't consistently achieved under dryland conditions.

While results from Chapters 2-4 demonstrate that tropical forage legumes can provide significant amounts of N under non-water limited conditions, maximising these potential benefits in dryland systems requires careful management of both the legume rotation and subsequent crops. For the legume rotation, this includes establishing legumes on soils with low N fertility, maximising plant available water and effective nodulation (Bell et al. 2017; Peoples et al. 2012). Critically, the subsequent crop must also have sufficient yield potential to take advantage of the additional legume N (Bell et al. 2017), which includes suitable sowing density and managing competition for N and soil water (Chapter 4). Similarly, Roxburgh and Rodriguez (2016) demonstrated that poorer performing farmers receive less benefit from increasing N inputs and should instead improve agronomic practices such as row spacing and sowing dates before they invest in providing additional N to their crops. Despite such management improvements, P and S deficiencies (Chapter 4), which are common in the tropics (Blair et al. 1980; Dabin 1980), may also limit legume production and maize yield responses. This is particularly important given the field experiment (Chapters 2 and 3) was on a more fertile Vertosol soil, rather than the highly weathered soils that are common in the tropics (Dabin 1980). Such deficiencies may contribute to the yield gap between simulated and actual on-farm yields (Chapter 4), indicating that there is a range of soil, climatic and management factors that limit on-farm forage legume and crop production.

Preferences to use legume biomass as fodder (Chapter 6, Giller et al. 2009) indicate that, under a cut and carry system, dual soil N-fodder benefits are unlikely to be achieved (Chapter 3-4). While these preferences are likely to continue given the large competition for biomass (Dixon et al. 2010), high levels of soil degradation (Lal 2004) and N input costs (Ngongo 2011) may increase the importance of achieving dual soil N-fodder benefits. Realising dual soil N-fodder benefits on-farm are particularly important given farmers commonly prefer legume technologies that provide multiple benefits (Chapter 6, Snapp et al. 2002, Giller. 2001). Although cutting and removing all biomass for fodder is likely to provide little N benefit to the subsequent crop (Chapter 3-4), there are other management options where dual benefits may be achieved. Grazing, rather than cutting and removing fodder, can more than double net inputs for fixed N (Peoples et al. 2012). Where cut and carry systems are the only suitable option, simulations (Chapter 4) indicate that under conditions that enable high legume biomass production but limit crop yield potential, a portion of legume biomass could be removed for fodder without reducing the yield benefit to the subsequent crop. In fact, farmers are unlikely to be able to remove all legume shoot biomass for fodder and hence may leave sufficient biomass to provide a small yield benefit. Despite this, food secure farmers may not benefit from increasing maize yield as it is not an economically valuable crop; rather they may prefer to allocate legume N to cash crop or livestock production. Thus, there is a range of biomass management options that provide flexibility for farmers to respond to changes in input costs and commodity prices and to adapt legume management to meet their production objectives.

While results indicate that large yield benefits are achievable, further research is needed to quantify the net inputs of fixed N and yield impacts for different management options including, relays, intercropping and pasture cropping (planting maize into a permanent stand of legumes; Chapter 5 and 6) and the proportion of biomass removed. Notably, improved understanding of the proportion of legume N allocated below ground for key tropical species and the impact of biomass removal on below ground legume N will help determine how the N benefits to the whole farming system can be maximised. At the whole farm level, the net inputs of reactive N from both fertiliser and biological fixation (new-fixed N) can be used to determine the quantity of new-fixed N used per unit of output, providing an indication of the N-use efficiency of mixed crop-livestock systems (Gerber et al. 2014). Combined with economic analysis this could provide insight into the efficiency and economic impacts of the range of legume management options available to farmers. This includes identifying whether legume N is best used as a soil ameliorant or fodder and how biomass management and targeting specific classes of livestock affect N-use efficiencies and income. In addition, such analysis could identify when the opportunity cost of forage legume production was higher than the cost of synthetic fertiliser or other fodder options, and how the N-use efficiencies compare between different fodder and soil amelioration technologies. Given low resource-use efficiency often results in high environmental impacts (Herrero et al. 2015), improved understanding on N-use efficiency at a farm level can also reduce environmental impacts.

7.2. Forage legume management affects whole farm production and income

Understanding the impact of forage legumes at farm level requires consideration of agro-ecological, socio-cultural and economic factors (Ojiem et al. 2006), yet there has been little research linking forage legume productivity with the fundamental properties of farming systems and the potential whole farm impacts. In fact, research has largely focused on agronomic performance (Giller 2001; Peoples et al. 2012; Peoples and Herridge 1990; Sumberg 2002; Whitbread and Pengelly 2004), and thus, under diverse farming conditions, forage legumes are unable to consistently or cost effectively deliver meaningful increases in soil fertility or animal production (Sumberg 2002). Chapter 5 focused on designing forage legume options which fit the fundamental system properties, including agro-climatic conditions as well as the economic and social context. This research quantified the impact of a range of forage legume management options on fodder quality, livestock production and whole farm income for six case study farms. Case study farmers were also engaged in participatory modelling to provide a better insight into farmers constraints and to provide context to the potential role of forage legumes in crop-livestock systems (Defoer et al. 1998; Sterk 2007).

In Chapter 5, the impact of legume management on livestock production and income was assessed using farming systems simulations and participatory modelling. Simulations indicated that forage legumes can provide large economic benefits, potentially more than doubling whole farm income without increasing downside risk. However, the production and economic impacts depended on legume management, herd size and composition, land availability and farmer preferences. Management options that integrated forage legumes with staple crops or used unutilised land had the largest economic benefit as, at current prices, there was no incentive to replace food crops with fodder. Herd size affected the marginal value of feed, which was higher for large herds (>2 TLU; 1.8-3.1 M Rp/t TLU^{-1}) than for small herds (<2 TLU, 0.9-1.0 M Rp/t TLU^{-1}). While bull intensification can increase income, it is likely to have a larger economic benefit if forage legumes are selectively fed. Notably, farmers' preferences indicated that only 10-50% of the maximum potential economic gain is likely to be achieved on-farm. This indicates that the *potential* economic impact quantified by simulations greatly overestimated the benefits that are likely to be achieved on farm. Thus, the assumptions underpinning the model provided unrealistic estimates of the benefits of forage legumes when sensibility tested with farmers. It is likely this disparity is due to differences between how the model and farmers deal with risk and variability. Accounting for this disparity in future whole farm modelling is critical to understanding the accuracy, relevance and application of modelling activities.

While forage legumes can provide significant economic benefits, the benefits achieved on farm are limited by resource availability – particularly land and labour – and farmers' production objectives. Consequently, livestock focused farmers with sufficient land, labour and capacity to invest are more likely to invest in larger areas of forage legumes and thus will receive the largest financial benefit. This is particularly applicable when a larger proportion of household income is derived from agricultural activities than from off farm income. However, farmers often have insufficient understanding of how best to manage new resources (Giller et al. 2011) and thus will require considerable support to develop the technical capacity to maximise the units of output per input of new-fixed N (Gerber et al. 2014). For households with smaller herds, considerable economic benefits were achievable however, poorer farmers may still not be able to invest in forage legumes. This is because poorer households commonly need to use their labour to generate income and are unable to invest in a labour demanding technology (Giller et al. 2011), such as forage legumes (Chapter 5 and 6). Forage legumes may also compete with crops which have a direct economic yield for food or sale (Giller et al. 2009), demonstrating that under land or labour constrained conditions the opportunity cost of forage legume production may be too high.

While results in Chapter 5 indicate that forage legumes can provide substantial economic benefits, the scope of this study was limited to farming system and household level analysis for six case study farms. Thus, the potential impacts at a micro and macro scale for a broader range of individual households and farm types remain uncertain. At a micro level, this requires consideration of intra-household interactions, including labour, which farmers indicate is the key constraint to adoption (Chapter 5 and 6). This is particularly important given reports that, while forage legumes can reduce cut and carry labour by 1-1.5 hours/day (Ahmed 2012; Connell et al. 2010; Maxwell et al. 2012), improved forages can also reduce labour-use efficiency (Komarek et al. 2015). Building on this, elucidating changes in resource-use efficiency for other resources, such as land and new-fixed N, and the trade-offs with food security and profit would help develop a more robust range of forage legume management options. For example, for different farm types, it remains unclear as to whether more consistent production and economic benefits can be achieved when forage legume biomass is allocated to livestock rather than to increasing soil N. At the farm level, understanding the impact on intercrops is critical to better elucidating the impacts on food self-sufficiency and nutritional security. Calculating the land equivalent ration

(LER), which is the land required to produce the same yield for sole crops compared to intercropping (Wiley 1979), for different forage legume management options would help explain these potential impacts. At a marco level, simulations which consider forecast changes in market access, input costs, commodity prices, resource availability, climate and environmental impacts can provide a clearer indication of adoption trajectories and impacts at a regional or national level (Herrero et al. 2014; Thornton and Herrero 2015). Such analysis is important, as Giller et al. (2011) indicates that both farms and farming systems are continually evolving.

7.3. Forage legume impacts are unevenly distributed between men and women

In addition to the agro-ecological, economic and social factors described above, socially constructed gender roles also affect the adoption of legume technologies and the distribution of positive and negative impacts (Kiptot et al. 2014; Snapp and Silim 2002). Differing household responsibilities mean men and women also use different criteria when evaluating legume technologies (Snapp and Silim 2002) and thus may favour different technologies or management options. Yet, there has been little assessment of how gender affects forage legume adoption and the distribution of positive and negative impacts (Paris 2002; Snapp and Silim 2002). Farmers livelihood strategy, which is driven by agro-ecological factors, material and social resources, markets, production objectives and attitudes towards risk, also define the range of options available to farmers (Butler et al. 2013; Scoones 2009; Tittonell et al. 2010). Thus, in Chapter 6, participatory research based on gender disaggregation and farm typologies assessed the distribution of benefits and trade-offs of forage legume production and whether men and women prefer different management options. The comparative value of forage legumes compared to grain and tree legumes was also assessed to determine the complementary or competitive nature of these technologies.

In Chapter 6, participatory evaluation of forage legumes indicated that the benefits and constraints of forage legume production differ for men and women. While fodder was the most important benefit, women also identified reduced labour savings and soil fertility as key benefits, while men focused more on financial benefits. To achieve these benefits, women preferred to integrate legumes with maize crops, while men favoured a single stand forage legumes so as to maximise biomass production and financial benefits, indicating women favoured a higher level of integration between crop and livestock enterprises. Whilst farmers were interested in seed sales, there is currently no formal seed market in West Timor and thus they are unlikely to remain a key benefit. Agro-climatic conditions also affected the importance of forage legume benefits, with soil fertility a more important benefit at highland sites, where median maize yields were lowest (Chapter 4). Despite these benefits, labour is the key constraint to adoption indicating that social and human capital, rather than natural and physical capital, are likely to constrain adoption. Participants indicated that grain or tree legumes may help overcome labour constraints or provide a more suitable option given resource availability and household objectives. For food insecure households, women commonly favoured grain legumes over forage or tree legumes, while men across all farm types favoured either forage or tree legumes.

While farmers indicated that forage legumes can provide meaningful benefits, socially constructed gender roles will influence forage legume adoption and the distribution of impacts. Uneven distribution of labour indicates that, for households with both men and women, there is the potential for forage legumes to negatively affect women's labour requirements and positively affect men's. This is particularly important given urban migration by men seeking employment may further increase women's labour burden (Djoeroemana et al. 2007). Thus, forage legume adoption requires a reallocation of labour or labour saving technologies, and for women to be able to share in the benefits (Doss 1999). This is critical as women's significant labour constraints and household responsibilities (Oedjoe 2006) mean that, for poorer farmers, the opportunity cost for fodder production, at the expense of food or cash crops, may be too high. In fact, women in food insecure households consistently favoured grain legumes over forage or tree legumes (Chapter 6). In contrast, men consistently favoured fodder production over grain legumes regardless of farm type. Under resource constrained conditions this potential conflict between grain and fodder production means that multipurpose varieties of cowpea, which produce large amounts of biomass and have good grain yields, may be a more suitable option (Giller 2001; Sanginga et al. 2001). Critically, it also demonstrates that, while a range of 'best bet' options or technologies must fit the specific socio-ecological niches of a diverse range of farming systems (Giller et al. 2011), they must also fit the constraints and preferences of male and female farmers within a household.

Significant labour constraints indicate that options which increase labour-use efficiency are critical to intensifying crop-livestock systems. For forage legumes, developing options that reduce labour inputs for planting and weeding are most critical. Alternatively, where there is sufficient rainfall or residual soil water, the timing of forage legume production could be moved so it doesn't compete with labour required for food crop production. Research is currently underway addressing both of these issues (ACIAR 2017). While this research did not consider female headed households, they are commonly more labour constrained (Quisumbing et al. 2014) and thus it is unlikely that they will be able to adopt such a labour intensive technology. In addition, understanding household labour impacts will also require consideration of labour inputs for children and elderly household members. Quantifying the labour-use efficiency for a range of forage and soil amelioration technologies could also provide insight into why farmers often preferred grain or tree legumes over forage legumes. This is particularly important as it remains to be seen whether farmers in West Timor have the capacity to plant sufficient areas of forage legumes to achieve meaningful – from the farmers' perspective – increases in crop or livestock production.

8. Conclusions and further research

This research advanced our understanding of the role forage legumes can play in intensifying smallholder crop-livestock systems. It demonstrated that, while significant production and economic benefits are achievable, large trade-offs associated with labour, land use and gender based production preferences determine the potential adoption trajectories and the distribution of impacts within a household. It also demonstrated that a combination of methods is required to develop a range of forage legumes options which suit the socio-economic conditions of a range of farming systems. Key findings of this thesis were:

1. Smallholder farmers' preferences to use forage legumes for fodder indicate that legume N benefits are likely to increase livestock production but not crop production. To maximise these benefits, legume management must minimise the impact on labour and food crop production and thus forage legumes are best managed as a permanent stand on unutilised land or integrated into cropping systems as relays or intercrops (Chapters 2-6).
2. Livestock focused farmers with sufficient land, labour and capacity to invest are likely to receive the largest economic benefits from forage legume production. Yet, in dryland systems, such farmers may favour tree legumes because of the potentially low labour inputs and the multiple fodder and subsistence benefits provided (Chapters 5 and 6).
3. Socially constructed gender roles determine the distribution of forage legume impacts. Thus, while forage legumes may provide large production and economic benefits (Chapter 5), unequal distribution of impacts within the household may

benefit one household member (predominantly men) while having a small or negative impact on another (predominantly women, Chapter 6).

4. Understanding the potential socio-ecological niche for forage legumes, as well as other technologies, requires the integration of agronomic, farming system and gender based research.

Major limitations of this research were the geographical separation of field experiments (Australia) and on-farm evaluation (Indonesia), the scale of the study and the limited validation of on-farm crop and livestock production benefits. While the separation of field experiments was done to enable intensive measurement of legumes and subsequent crop production, field experiments in West Timor will be required to further validate potential production and farming system impacts for the environmental conditions experienced in Eastern Indonesia. It is also recommended that future forage legume research assesses the impact of forage legumes for a larger number of individual farmers and a broader range of farming systems. This would provide insight into the potential production and economic benefits for a larger number of farmers. Participatory research could be further strengthened by measuring on-farm production including biomass production, changes in cattle liveweight, staple and intercrop production and labour inputs. Combined with controlled field experiments in West Timor, such measurements could validate farming systems simulations and quantify impacts against which farmers could assess the benefits of forage legumes at a household and intra-household level. Critically, an effective forage legume seed market will also be required to achieve the benefits described in this thesis as forage legumes can not be vegetatively propagated.

In addition, there are a range of important factors beyond the scope of this study which could contribute to the further development of forage legume technologies. Firstly, there is significant scope to explore the role of forage legumes in a broader range of farming systems. This includes annual rice production systems, where perennial forages can compete with annual crops (Chapter 6). This could increase land and water use efficiency in systems where there is sufficient residual soil water or irrigation for forages but not a second food crop. There is also significant scope for further research in land constrained systems as synergies between crop and livestock enterprises are unlikely to increase unless there is sufficient pressure on resources. Secondly, we also require a better understanding of the trade-offs between using forage legumes for fodder and increasing soil fertility on smallholder farms, as these have only been tested using field experiments and simulations. Options that mitigate these trade-offs and enable the combined benefits of high quality fodder and improved soil fertility will increase the adoption potential of forage legumes. Third, further improvement and validation of the APSIM forage legume model is required to enable forage legumes to be simulated with greater confidence in a wider range of environments and farming systems. This could then allow for more comprehensive simulations that assess key management factors such as the amount of biomass available for fodder if a certain maize yield is targeted, different cutting regimes and the synchronisation of N release with crop N demand and climatic risk. Fourth, upscaling the research to include landscape, regional and national scales can help determine trajectories of intensification, diversification or stagnation (Herrero et al. 2014) and identify different farming systems where forage legumes may be a suitable investment. Finally, Herrero et al. (2015) indicates that “efficient, equitable and gender-sensitive pathways” are required to enable farmers to transition to more sustainable livestock systems. Thus, further development of forage legume technologies requires an understanding of the transitional steps which farmers can take to intensify their crop-livestock systems.

Beyond West Timor, this study demonstrates that forage legumes can provide significant production and economic benefits to smallholder farmers. Yet, the large trade-offs associated with forage legume management, and diversity of farming systems that exist, indicate that a range of forage legume options must be developed which farmers can adapt to suit their specific agro-climatic and socioeconomic conditions. Critically, these options should be presented with alternative fodder or soil amelioration technologies, as the potential socio-ecological niche for forage legumes is limited by resource availability and production preferences. Finally, in addition to understanding the farming systems, forage legume development requires consideration of gender relations and the distribution of impacts within the household

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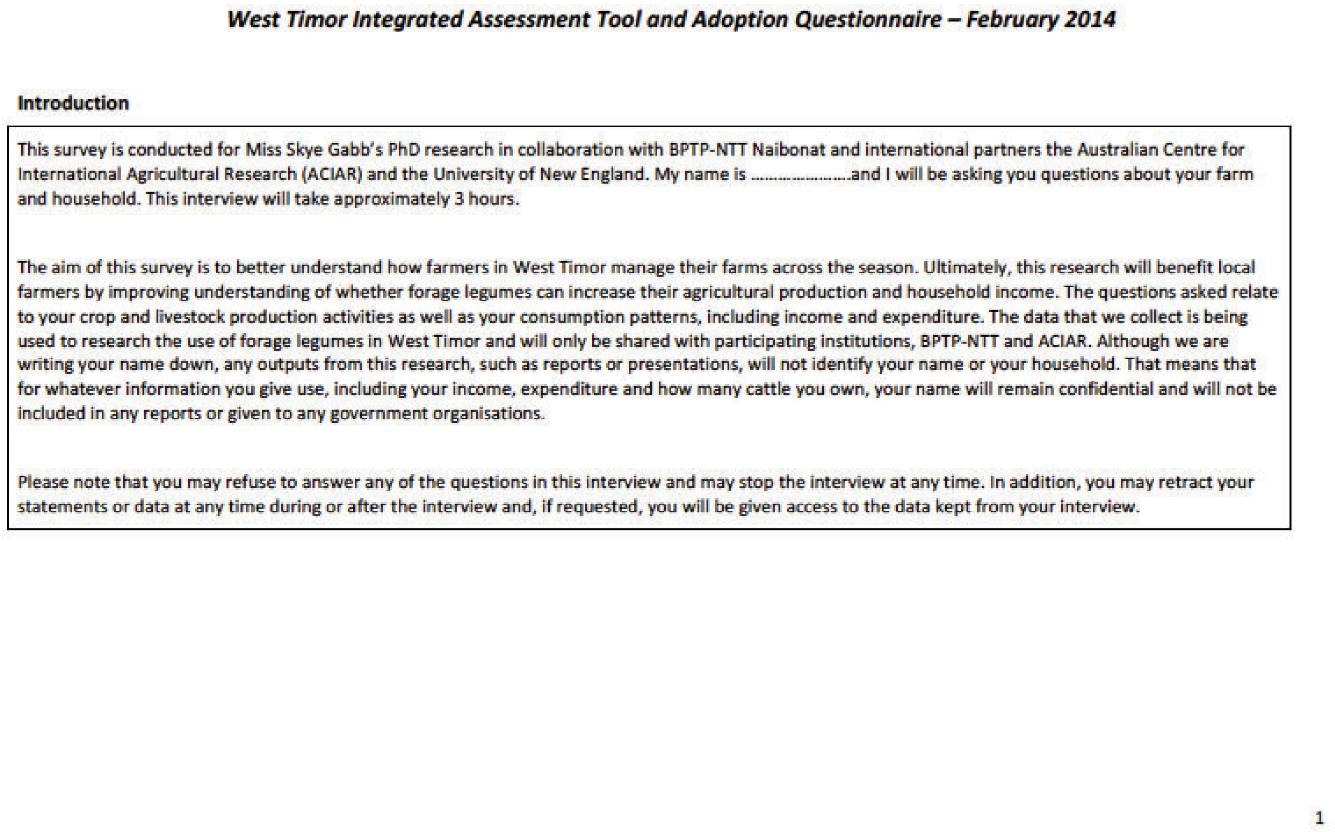
Appendix 1 Household questionnaire for IAT parameterisation



West Timor Integrated Assessment Tool and Adoption Questionnaire – February 2014

Introduction

This survey is conducted for Miss Skye Gabb's PhD research in collaboration with BPTP-NTT Naibonat and international partners the Australian Centre for International Agricultural Research (ACIAR) and the University of New England. My name is …………………and I will be asking you questions about your farm and household. This interview will take approximately 3 hours.

The aim of this survey is to better understand how farmers in West Timor manage their farms across the season. Ultimately, this research will benefit local farmers by improving understanding of whether forage legumes can increase their agricultural production and household income. The questions asked relate to your crop and livestock production activities as well as your consumption patterns, including income and expenditure. The data that we collect is being used to research the use of forage legumes in West Timor and will only be shared with participating institutions, BPTP-NTT and ACIAR. Although we are writing your name down, any outputs from this research, such as reports or presentations, will not identify your name or your household. That means that for whatever information you give use, including your income, expenditure and how many cattle you own, your name will remain confidential and will not be included in any reports or given to any government organisations.

Please note that you may refuse to answer any of the questions in this interview and may stop the interview at any time. In addition, you may retract your statements or data at any time during or after the interview and, if requested, you will be given access to the data kept from your interview.

1

Interview

Interviewer	
Date of interview	

Village and identifying information

1.	Name of interviewee/s	
2.	Farmer group	
3.	Village	

Household information

4. *To help us understand the best way you could use forage legumes we need to know how many people there are in your household and how much labour they can provide. This will help us understand how much labour is available to manage legumes and how much labour can be saved while collecting feed during the dry season.*

How many males and females do you have living in your household (including head), and how many full days labour dothey contribute each week?

		Adults (20-65)		Teens (13-19)		Children (<13)		Elderly (>65)	
		Male	Female	Male	Female	Male	Female	Male	Female
a.	Number in household								
b.	Labour availability(full days/week per person)								

Land use and ownership

5. *We will now talk about your land and the crops that you grow. It is important that we collect this information so that we can understand where you could plant legumes on your farm.*

a. How many parcels of land do you have?..

(For each parcel of land then fill in the table)

Land parcel	(a) Type of land[1]	(b) Area (are)*	(c) Distance from house (meters)	(d) Water source[2]	(e) Owned (O) or Rented (R)	(f) Type of rent[3]	(g) Cost of rent (Rp)	(h) Crops, forages, pastures or trees grown
Parcel 1					O/R			
Parcel 2					O/R			
Parcel 3					O/R			
Parcel 4					O/R			
Parcel 5					O/R			

[1] House yard; Crop; Pasture; Forest/tree plantations; other

[2] R = rainfed; PI = partially irrigated; FI = full irrigation

[3] B=borrowed; L=Leased;S=sharecropping;O=other, specify

*10 x 10m

Crops, forages, pastures, fertilisers and yields

6. *We will now talk about what crops and forages you grow.* Inthe **2013-2014**season, what crops and forages did you grow?*(For each crop then fill in the table)*

Input	**Crop/forage 1**	**Crop/forage 2**	**Crop/forage 3**	**Crop/forage 4**	**Crop/forage 5**	**Crop/forage 6**
Crop/forage Name						
Sole crop (S) or intercropped (I)						
If intercropped, with what crops?						
Area cropped (are)						
Crop planted after harvesting this crop						
Area of subsequent crop (are)						
Yield (kg or ikat)						
Kept for consumption/seed (kg)						
Value of grain/vegetables sold (Rp/kg)						
Residue production (kg)						
Residue use[1]						

[1] incorporated in soil (I); burned (B); used for mulch (M); used for grazing (G); used for cut and carry (CC); other (O)

7. For the crops you described above, we will now talk about the inputs you used in the **2013-2014**season *(fill in the table for each crop)*

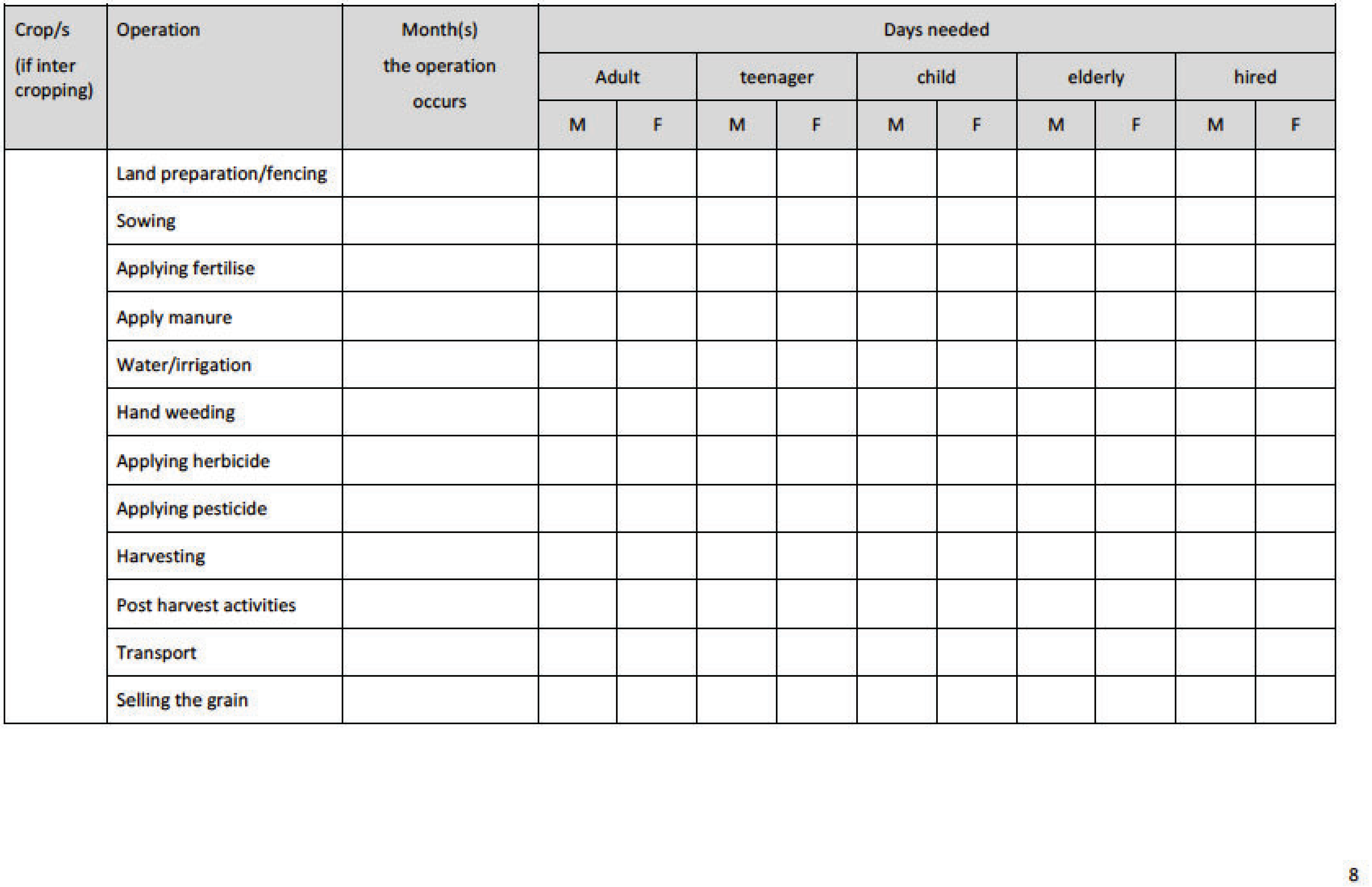
Input	**Crop/forage 1**	**Crop/forage 2**	**Crop/forage 3**	**Crop/forage 4**	**Crop/forage 5**	**Crop/forage 6**
Crop/forage name						
Seed planted (kg/are)						
Seed cost (Rp/kg)						
Fertiliser A name						
Fertiliser A kg/are						
Fertiliser A Rp/kg						
Fertiliser B name						
Fertiliser B kg/are						
Fertiliser B Rp/kg						
Chemical name						
Chemical (L or kg/are)						
Chemical cost (Rp/kg or L)						
Manure use (kg/are)						
Manure Rp/kg						
Irrigation (Rp/year)						

8. *For the crops we've just talked about, I would now like to ask you about how much labour is required to produce these crops.*

For the **2013-14** season, what were your labour requirements for cropping and forage activities (man days/ha)?

Crop/s (if inter cropping)	Operation	Month(s) operation occurs	Days needed									
			Adult		Teenager		Child		Elderly		Hired	
			M	F	M	F	M	F	M	F	M	F
	Land preparation/fence											
	Sowing											
	Applying fertilise											
	Apply manure											
	Water/irrigation											
	Hand weeding											
	Applying herbicide											
	Applying pesticide											
	Harvesting											
	Post harvest activities											
	Transport											
	Selling the grain											

Crop/s (if inter cropping)	Operation	Month(s) the operation occurs	Days needed									
			Adult		Teenager		Child		Elderly		Hired	
			M	F	M	F	M	F	M	F	M	F
	Land preparation/fencing											
	Sowing											
	Applying fertilise											
	Apply manure											
	Water/irrigation											
	Hand weeding											
	Applying herbicide											
	Applying pesticide											
	Harvesting											
	Post harvest activities											
	Transport											
	Selling the grain											



Crop/s (if inter cropping)	Operation	Month(s) the operation occurs	Days needed									
			Adult		teenager		child		elderly		hired	
			M	F	M	F	M	F	M	F	M	F
	Land preparation/fencing											
	Sowing											
	Applying fertilise											
	Apply manure											
	Water/irrigation											
	Hand weeding											
	Applying herbicide											
	Applying pesticide											
	Harvesting											
	Post harvest activities											
	Transport											
	Selling the grain											

8

9. Are the labour requirements you just described for 2013-14lower, average or higher than most years?

(a) Lower	(b) Average	(c) Higher

10. Is the **yield**for the crops in 2013-14 lower, average or higher than what you harvestin most years?

(a) lower	(b) average	(c) higher

11. *To help us understand how forage legumes could benefit your household, we would like to ask you about your household's food security.*
How often do you harvest enough maize to feed your family until the next harvest?

(a) Every year	(b) Most years	(c) Half the time	(d) Never	(e) Don't know

12. What month or months do you normally have the least amount of food available to feed to your household?

Month/s:

13. Do you regularly help other farmers in your farmer group?

(a) Yes	(b) No

If yes, how many days each month do you spend helping other farmers?

Month	Adult		Teenager		Child		Elderly	
	M	F	M	F	M	F	M	F
January								
February								
March								
April								
May								
June								
July								
August								
September								
October								
November								
December								

Tree crops

14. What tree crops do you plant(including tree legumes)?

		Tree 1	Tree 2	Tree 3	Tree 4
a.	Tree name				
b.	Area (ha) / number of trees				
c.	Where planted[1]				
d.	Total yield fruit/nut (kg/year)				
e.	Value (Rp/year)				
f.	Yield of by-product (e.g. leaves) (kg/year)				
g.	Value of by-product (Rp/year)				
h.	Kept for home consumption (kg)				
i.	Labour requirements (Dec-Feb days/tree or per ha)				
j.	Labour requirements (Mar-May days/tree or per ha)				
k.	Labour requirements (Jun-Aug days/tree or per ha)				
l.	Labour requirements (Sept-Nov days/tree or per ha)				
m.	Who does the labour[2]				

[1] Bund (B), Living fence (LF), Single stand (S), Other (O) describe

[2] Men only (M), women only (W), men and women (MW), whole family (W)

Livestock

15. *We will now focus on your livestock. It is important to collect information about how many livestock you have because it will help us understand how much you could benefit from forage legumes. Remember that we will not be sharing your name and the number of livestock you personally own with anyone else.*

(fill in the table for each type of livestock the farmer has)

Type of animal	**Owned**	**Owned but managed by others**	**Managed but owned by others**	**Payment[1]**		**Body weight (kg)**	**Purpose owned[1]**
				Cash (Rp/yr)	**In kind**		
Cattle							
Bulls							
Breeding Cows							
Heifers (<2yo)							
Young males (<2 yo)							
Calves							
Goats							
Billies							
Breeding does							
Young does (<1 yo)							
Young males (<1 yo)							
Kids							

[1] Purpose of rearing livestock, (H=Household consumption, I=Extra-income, D=Draught, O=Others, please specify)

Type of animal	Owned	Owned but managed by others	Managed but owned by others	Payment[1]		Average weight (kg)	Purpose owned[1]
				Cash (Rp)	In kind		
Other animals -							
Pigs							
Chickens							
Other:							
Other:							

[1] Purpose of rearing livestock, (H=Household consumption, I=Extra-income, D=Draught, O=Others, please specify)

Animal marketing

16. *To help us understand how legumes could potentially increase the body weight and sale value of your livestock, we need to know how many livestock you sell and what price you get.*Please describe your livestock production levelsduring the previous year.

	SALES	**Cattle**	**Goats**	**Other**	**Other**
a.	Number sold				
b.	Type				
c.	Price (Rp/animal)				
d.	Size of animal/s (kg)				
e.	Reason sold[2]				
	PURCHASES				
f.	Number purchased				
g.	Type[1]				
h.	Price (/kg)				
i.	Size of animal (kg)				
	DEATHS				
j.	Number				
k.	Type[1]				

[1] e.g. Bull; cow; calf; heifer etc

[2] Regular source of income; Special occasion; Necessity; Other

17. Is the number of livestock **sold** in the past yearlower, average or higher than most years?

(a) lower	(b) average	(c) higher

18. Is the number of livestock**purchased** in the past yearlower, average or higher than most years?

(a) lower	(b) average	(c) higher

19. Is the number of livestock that **died** in the past yearaverage, higher or lower than most years?

(a) lower	(b) average	(c) higher

Cattle and goat management breeding management

(fill in the table)

		Cattle			Goats		
20.	What month/s is the usual time of birth?						
21.	Does the time of birth vary much from year to year?	(a) Yes	(b) No		(a) Yes	(b) No	
22.	What is the common interval (in months) between births?						
23.	Weaning age (months)						
24.	What month are calves normally weaned?						
25.	After weaning, are breeders and weaners fed the same feed?	(a) Yes	(b) No		(a) Yes	(b) No	
26.	Do you ever have surplus livestock to sell?	(a) Yes	(b) No		(a) Yes	(b) No	
27.	Is yes, whatis the criteria for selling males and **surplus** females, Age or Weight?	(b) Age	(b) Weight		(a) Age	(b) Weight	
28.	What Age/Weight?						
29.	If breeders fail to give birth, are they culled/sold?	(a) Yes	(b) No		(a) Yes	(b) No	
30.	If culled, how are they replaced[2]?	(a) Purchased	(b) Kept from another cow	(c) Not replaced	(a) Purchased	(b) Kept from another cow	(c) Not replaced

31. How does you grazing management for cattle and goats change across the year?

	Animal type	**Wet season** **January-April**	**Late wet-early dry** **May-July**	**Late dry season** **August-December**
	Cattle type	**Grazing management**[1]		
a.	Bull			
b.	Cow			
c.	Heifer (<2 yo)			
d.	Young male (<2 yo)			
e.	Calf			
	Goats type[2]	**Grazing management**[1]		
f.	Billies			
g.	Breeding does			
h.	Young does (<1 yo)			
i.	Young males (<1 yo)			
j.	Kids			

[1] Free grazing (FG), Mobile tethered grazing (TG), Feedlot (FL), Cut and carry (CC)

32. Where are the cattle at night-time?

33. Are pen/feedlot fed cattle fed together or are some fed separately?

(a) Fed together	(b) Some fed separately, which ones?...	(c) All fed separately

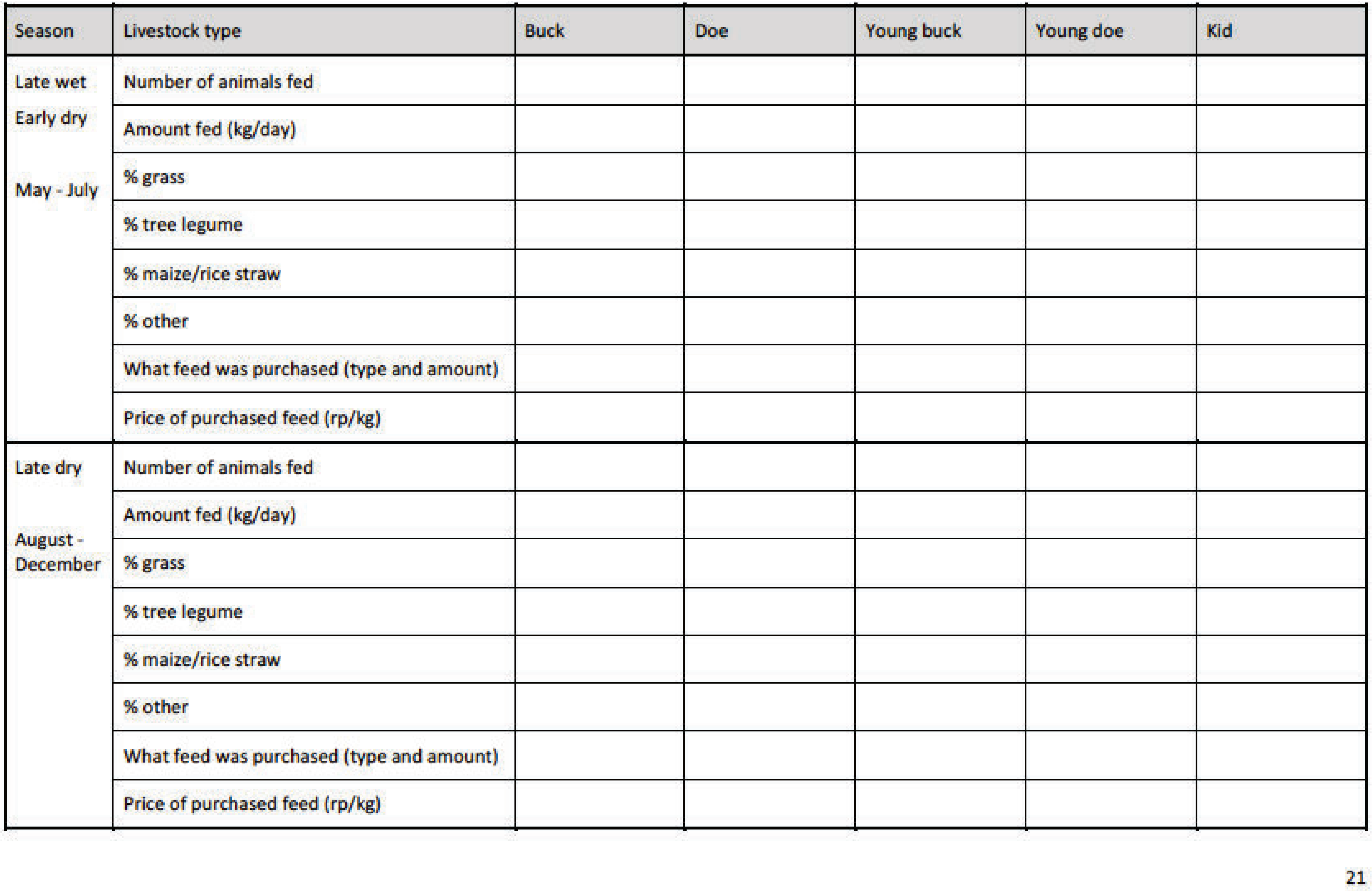
34. Could you describe what you feed your different types of**cattle** and how this changes over the year?

Season	Livestock type	Bull	Cow	Heifer	Young bull	Calf
Wet January-April	Number of animals fed					
	Amount fed (kg/day)					
	% grass					
	% tree legume					
	% maize/rice straw					
	% other					
	What feed was purchased (type and amount)					
	Price of purchased feed (rp/kg)					

Season	Livestock type	Bull	Cow	Heifer	Young bull	Calf
Late wet Early dry May - July	Number of animals fed					
	Amount fed (kg/day)					
	% grass					
	% tree legume					
	% maize/rice straw					
	% other					
	What feed was purchased (type and amount)					
	Price of purchased feed (rp/kg)					
Late dry August - December	Number of animals fed					
	Amount fed (kg/day)					
	% grass					
	% tree legume					
	% maize/rice straw					
	% other					
	What feed was purchased (type and amount)					
	Price of purchased feed (rp/kg)					

35. Could you describe what you feed your **goats** and how this changes over the year?

Season	Livestock type	Buck	Doe	Young buck	Young doe	Kid
Wet January - April	Number of animals fed					
	Amount fed (kg/day)					
	% grass					
	% tree legume					
	% maize/rice straw					
	% other					
	What feed was purchased (type and amount)					
	Price of purchased feed (rp/kg)					



Season	Livestock type	Buck	Doe	Young buck	Young doe	Kid
Late wet Early dry May - July	Number of animals fed					
	Amount fed (kg/day)					
	% grass					
	% tree legume					
	% maize/rice straw					
	% other					
	What feed was purchased (type and amount)					
	Price of purchased feed (rp/kg)					
Late dry August - December	Number of animals fed					
	Amount fed (kg/day)					
	% grass					
	% tree legume					
	% maize/rice straw					
	% other					
	What feed was purchased (type and amount)					
	Price of purchased feed (rp/kg)					

Livestock labour requirements and responsibilities

36. How many hours a day in **2014** did you spend looking after your **cattle**?

(fill in table)

Operation	Month(s) or season	Days or hours needed/Responsibility									
		child		teenager		adult		elderly		hired	
Labour requirements		M	F	M	F	M	F	M	F	M	F
Cut and carry in wet season (hrs/day)	January – April										
Cut and carry in early dry season (hrs/day)	May – July										
Cut and carry in late dry season (hrs/day)	August - December										
Collecting water (hrs/day)											
Taking animals to grazing area (hrs/day)											
Feeding/grooming (hrs/day)											
Controlling mating (days/year)											
Treating diseases (days/year)											

37. How many hours a day in **2014** did you spend looking after your **goats**?

(fill in table)

Operation	Month(s) or season	Days or hours needed/Responsibility									
		Adult		Teenager		Child		Elderly		Hired	
Labour requirements		M	F	M	F	M	F	M	F	M	F
Cut and carry in wet season (hrs/day)	January – April										
Cut and carry in early dry season (hrs/day)	May – July										
Cut and carry in late dry season (hrs/day)	August - December										
Collecting water (hrs/day)											
Taking animals to grazing area (hrs/day)											
Feeding/grooming (hrs/day)											
Controlling mating (days/year)											
Treating diseases (days/year)											

Inputs for animal production

38. In **2014**, what were your expenses for cattle and goat production?

Cost	Cattle	Goats
Purchased feed – cost (Rp/year)		
Veterinarian/medical costs (Rp/year)		
Other		

39. Are the costs described for 2014lower, average or higher than most years?

(a) Lower	(b) Average	(c) Higher

40. *I would now like to ask you some questions about your income. I am asking these questions because it will help us understand whether forage legumes can increase the income on your farm. Remember, that your name will remain completely confidential and will not be included in any publications or reports, that means that no one other that us that collect the data and the project team with ACIAR will know that it was you that gave us this information.*

a. Focusing on 2014 only, what were your main sources of family income,including on-farm and off-farm income?

	Source	Value (Rp)	% of total
a.	Crops		
b.	Livestock		
c.	Vegetables		
d.	Off farm employment		
e.	Government payments		
f.	Remittances		
g.	Credit/loans		
h.	Other		
i.	Other		
j.	Total		100

41. Was the **income**for **2014** aboveaverage, higher or lower than what you receivein most years?

(a) lower	(b) average	(c) higher

42. *I would now like to ask you about what you spend your money on. I am asking this question because I would like to know if planting forage legumes increases income how you might benefit from that increased income. For example, you might have more money to spend on education or to buy livestock.*

Focusing on 2014 only, what were your major farming and household cost?

	Cost	Cost (Rp)	% of total
a.	Education		
b.	Food		
c.	Clothes		
d.	Debt payment		
e.	Paying labourers		
f.	Health		
g.	Improving house		
h.	Farm inputs		
i.	Transport costs		
j.	Mobile phone		
k.	Church/Mosque		
l.	Other....................................		
m.	Other....................................		
n.	Total		100

43. Were the **costs**for 2014 lower,average or higher than what you spendin most years?

(a) Lower	(b) Average	(c) Higher

44. Related to your costs above, what month/s do you have the most difficulty getting enough cash to meet all you expenses?

Month/s:

45. *I would now like to ask you about your household and what you are currently trying to achieve for your family and farm. You might like to think about what you would like to have achieved in 5 years time compared to now. These might include producing more food for your family, you children finishing school, increasing your household income, increasing the number of cattle you own or there might be other more important things that you'd like to tell us about.*

a. Could you now please tell us what you are currently focusing on trying to achieve for your family and farm?

....

....

....

b. Of the things we've just discussed could you list in order the three most important things you are trying to achieve?

	Objective	Rank			Rank
a.	Produce enough food		e.	Maximise the number of livestock sold every year	
b.	Provide children's education		f.	Reduce labour requirements	
c.	Maximise total household profit		g.	Other...	
d.	Maximise the number of livestock the household owns		h.	Other...	

Previous legume use

46. *The next set of questions is specifically about herbaceous forage legumes. These are the plants that this project is about and we are interested in any previous experience you have had with them and you opinion about the potential benefits and constraints of planting these legumes on your farm.*

    Have you ever used forage legumes on your farm?

    (a) Yes ***(continue to question47)***
    (b) No ***(continue to question 61)***

47. Are you still using this forage legume?

    (a) Yes ***(continue to question 48)***
    (b) No ***(continue to question57)***

Currently using forage legumes

48. Which species are you currently using? ………………………………………………………………………………

49. What area is planted? (are) ……………………………………………………………………………………………

50. Are the forage legumes planted with trees/crops?

(a) Yes, if yes what trees/crops?………………………………………………………………………………
(b) No

51. How did you learn about forage legumes?

(a) Extension officer
(b) NGO (name………………………………………)
(c) Research officer
(d) Farmer in this village
(e) Farmer in another village
(f) Other……………………………………………

52. Why did you start planting forage legumes?

(a) To have more cattle feed
(b) To increase livestock growth rates
(c) To increase sale price of livestock
(d) To improve soil fertility
(e) To increase crop yield
(f) To increase income
(g) To increase household income
(h) To reduce labour requirements
(i) To reduce erosion
(j) Because extension/NGO gave me seed
(k) Other……………………………………………
Other……………………………………………

53. What are you currently using forage legumes for?

(a) Cattle feed
(b) Goat feed
(c) Selling to other farmers
(d) In crop rotation
(e) Human consumption
(f) Erosion control
(g) Other……………………………………………
(h) Other……………………………………………

54. What are the benefits?

(a) Increased cattle feed
(b) Increased livestock growth rates
(c) Increased sale price of livestock
(d) Increased crop yield
(e) Increased household income
(f) Reduced labour requirements
(g) Reduced erosion
(h) Other...
(i) Other...

55. What were the constraints to adopting these legumes?

(a) Access to information
(b) Current knowledge levels
(c) Access to seed
(d) Rainfall
(e) Disease
(f) Grazing by others animals
(g) Fence maintenance
(h) Labour availability/time required
(i) Slow growth of plants
(j) Land availability
(k) Other ....
(l) Other ....

56. What are your future plans for these forage legumes?

(a) Increase area
(b) Decrease area
(c) Stop using them
(d) Use them for another use (describe) ....

(Continue to question61)

Has previously used forage legumes but stopped

57. What legume did you plant? ……………………………………………………………………………………………………

58. What were the reasons you started planting the legume?

(a) To have more cattle feed
(b) To increase livestock growth rates
(c) To increase sale price of livestock
(d) To improve soil fertility
(e) To increase crop yield
(f) To increase income
(g) To increase household income
(h) To reduce labour requirements
(i) To reduce erosion
(j) Because extension/NGO gave me seed
(k) Other……………………………………………………
(l) Other……………………………………………………

59. What were the benefits?

(a) Increased cattle feed
(b) Increased livestock growth rates
(c) Increased sale price of livestock
(d) Increased crop yield
(e) Increased household income
(f) Reduced labour requirements
(g) Reduced erosion
(h) There were no benefits
(i) Other……………………………………………………

60. What were the reasons you stopped using them?

(a) Access to information
(b) Current knowledge levels
(c) Access to seed
(d) Rainfall
(e) Disease
(f) Grazing by others animals
(g) Fence maintenance
(h) Labour availability/time required
(i) Slow growth of plants
(j) Land availability
(k) Other ……………………………………
(l) Other ……………………………………

(Continue to question61)

PhD/ACIAR legume activities

(Ask all respondents the rest of the questionnaire)

The following questions all relate to the forage legume activities that we are running with your farmer group. The questions are about why your are interested in legumes, what you think the benefits might be, what might be difficult about planting legumes and what you plan to use the legumes for on your farm. Remember that there are lots of different ways to use legumes on your farm and we are interested in what ***you*** *want to do on your farm.*

61. Why do you want to plant forage legumes?

(a) To have more cattle feed
(b) To increase livestock growth rates
(c) To increase sale price of livestock
(d) To increase crop yield
(e) To increase income
(f) To increase household income
(g) To reduce labour requirements
(h) To reduce erosion
(i) Other...
(j) Other...

62. What forage legume/s are you planting this year? ....

63. Some types of legumes have different characteristics to other legumes, why did you choose this/these species?

(a) It will regrow after cutting
(b) Seed is easy to harvest
(c) It looks like it will grow well
(d) I had heard about/seen that legume before
(e) It looked like it would be good livestock feed
(f) You can eat the seeds
(g) To help control erosion
(h) Other..

64. Where are you planting the forage legumes?..

65. What area of land do you have prepared to plant the legumes? (are) ....

66. Are you planting the legumes with any other crops/trees?

(a) Yes, if yes what crops/trees?..

(b) No

67. Who in the household is making the decisions about where to plant and how to manage the legumes?

(a) Man only	(c) Man and women together
(b) Woman only	(d) Other. ....

68. Who in the household will provide the labour to plant and manage the legumes?
(Fill in the table by ticking the relevant boxes)

Activity	Adult		Teen (13-19)		Children (<13)		Elderly (>65)		Hired labour	
	M	F	M	F	M	F	M	F	M	F
Prepare land										
Plant										
Management (i.e.weeding)										
Feeding to livestock										

Perceptions and opinions about forage legumes

69. What do you understand to be the benefits of forage legumes?

(a) High livestock feed quality
(b) Increase livestock growth
(c) Increase sale price of livestock
(d) Increase household income
(e) Improve soil fertility
(f) Increase crop yield
(g) Reduce labour requirements
(h) Reduce erosion
(i) Other……………………………………
(j) Other……………………………………

70. In your opinion, what is:

a. Your awareness of the benefits of forage legumes?

1	2	3	4	5
No awareness	Low	Medium	High	Very high

b. Your confidence in using forage legumes?

1	2	3	4	5
No confidence	Low	Medium	High	Very high

c. Your current knowledge about how to grow and utilise forage legumes?

1	2	3	4	5
No knowledge	Low	Medium	High	Very high

d. Your access to information on growing and utilising legumes?

1	2	3	4	5
No access	Low	Medium	High	Very high

71. What do you consider to be the key constraints for using forage legumes?

(a) Access to information
(b) Current knowledge levels
(c) Access to seed
(d) Rainfall
(e) Disease
(f) Grazing by others animals
(g) Fence maintenance
(h) Labour availability/time required
(i) Slow growth of plants
(j) Land availability
(k) Other ……………………………………
(l) Other ……………………………………

72. How do you see your future use of forage legumes in your farming system?

………

………

………

………

Personal information

I would now like to ask you a few questions about yourself. Remember that your name will remain confidential so this information will not be reported identifying you or your family.

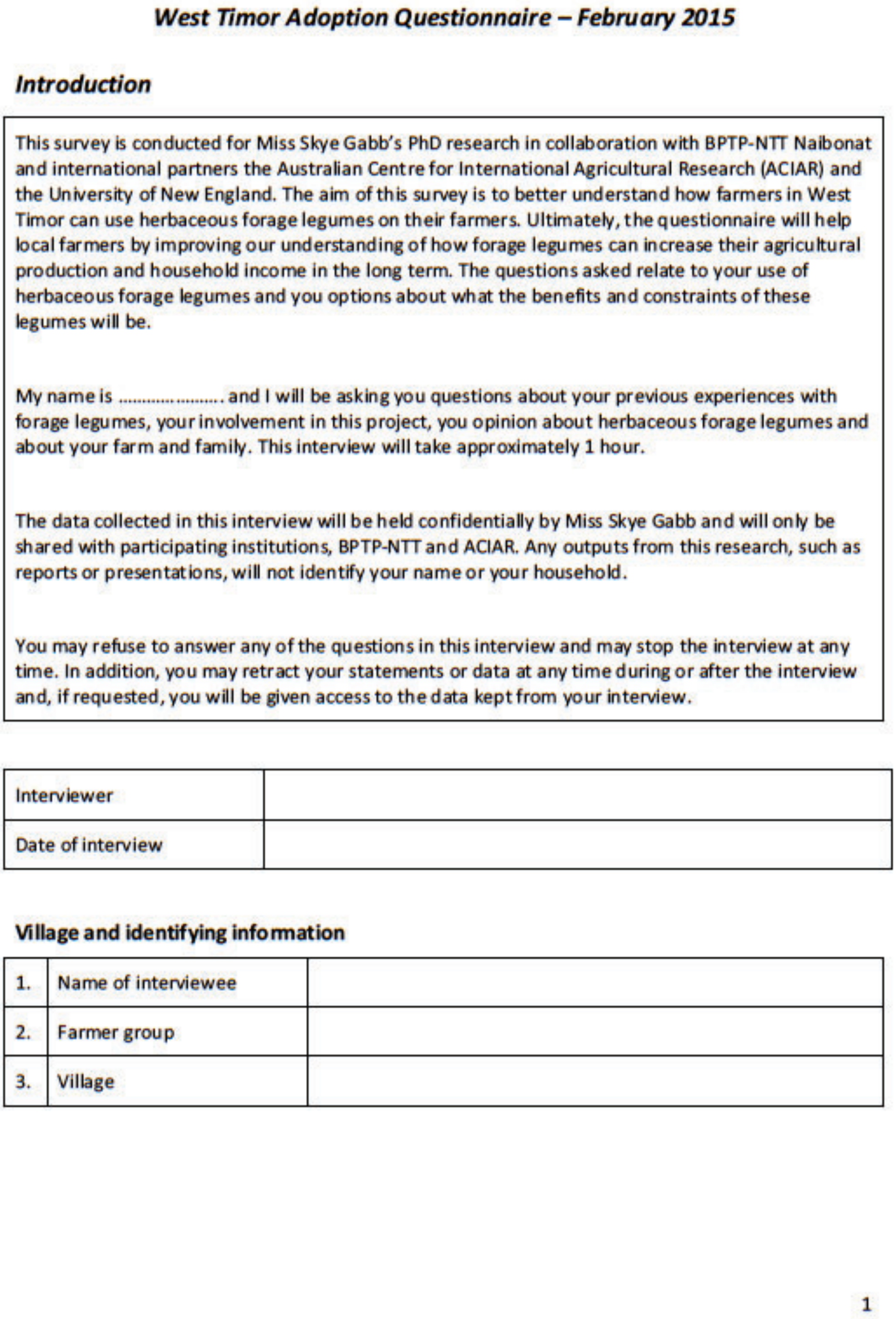
		Person 1	**Person 2**
1.	Sex	(a) Male (b) Female	(a) Male (b) Female
2.	Age		
3.	Marital	(a) Married (b) Unmarried (c) Widower/Widow (d) Other	(a) Married (b) Unmarried (c) Widower/Widow (d) Other
4.	Position in household	(a) Head of household (b) Spouse (c) Other	(a) Head of household (b) Spouse (c) Other
5.	Education level	(a) None (b) Primary (c) Middle (d) Secondary (e) University	(a) None (b) Primary (c) Middle (d) Secondary (e) University
6.	Is your main occupation farming?	(a) Yes (b) No	(a) Yes (b) No
7.	Other occupations		

Notes: ....

....

....

Appendix 2 Household questionnaire for farm characterisation



West Timor Adoption Questionnaire – February 2015

Introduction

This survey is conducted for Miss Skye Gabb's PhD research in collaboration with BPTP-NTT Naibonat and international partners the Australian Centre for International Agricultural Research (ACIAR) and the University of New England. The aim of this survey is to better understand how farmers in West Timor can use herbaceous forage legumes on their farmers. Ultimately, the questionnaire will help local farmers by improving our understanding of how forage legumes can increase their agricultural production and household income in the long term. The questions asked relate to your use of herbaceous forage legumes and you options about what the benefits and constraints of these legumes will be.

My name is ………………… and I will be asking you questions about your previous experiences with forage legumes, your involvement in this project, you opinion about herbaceous forage legumes and about your farm and family. This interview will take approximately 1 hour.

The data collected in this interview will be held confidentially by Miss Skye Gabb and will only be shared with participating institutions, BPTP-NTT and ACIAR. Any outputs from this research, such as reports or presentations, will not identify your name or your household.

You may refuse to answer any of the questions in this interview and may stop the interview at any time. In addition, you may retract your statements or data at any time during or after the interview and, if requested, you will be given access to the data kept from your interview.

Interviewer	
Date of interview	

Village and identifying information

1.	Name of interviewee	
2.	Farmer group	
3.	Village	

Previous legume use

4. Have you ever used forage legumes in your farming system?

(a) Yes ***(continue to question 5)***
(b) No ***(continue to question 8)***

5. Are you still using this forage legume?

(a) Yes ***(continue to question 6)***
(b) No ***(continue to question 7)***

Currently using forage legumes

(Answered yes to Q4 & Q5)

6. Which species are you currently using?

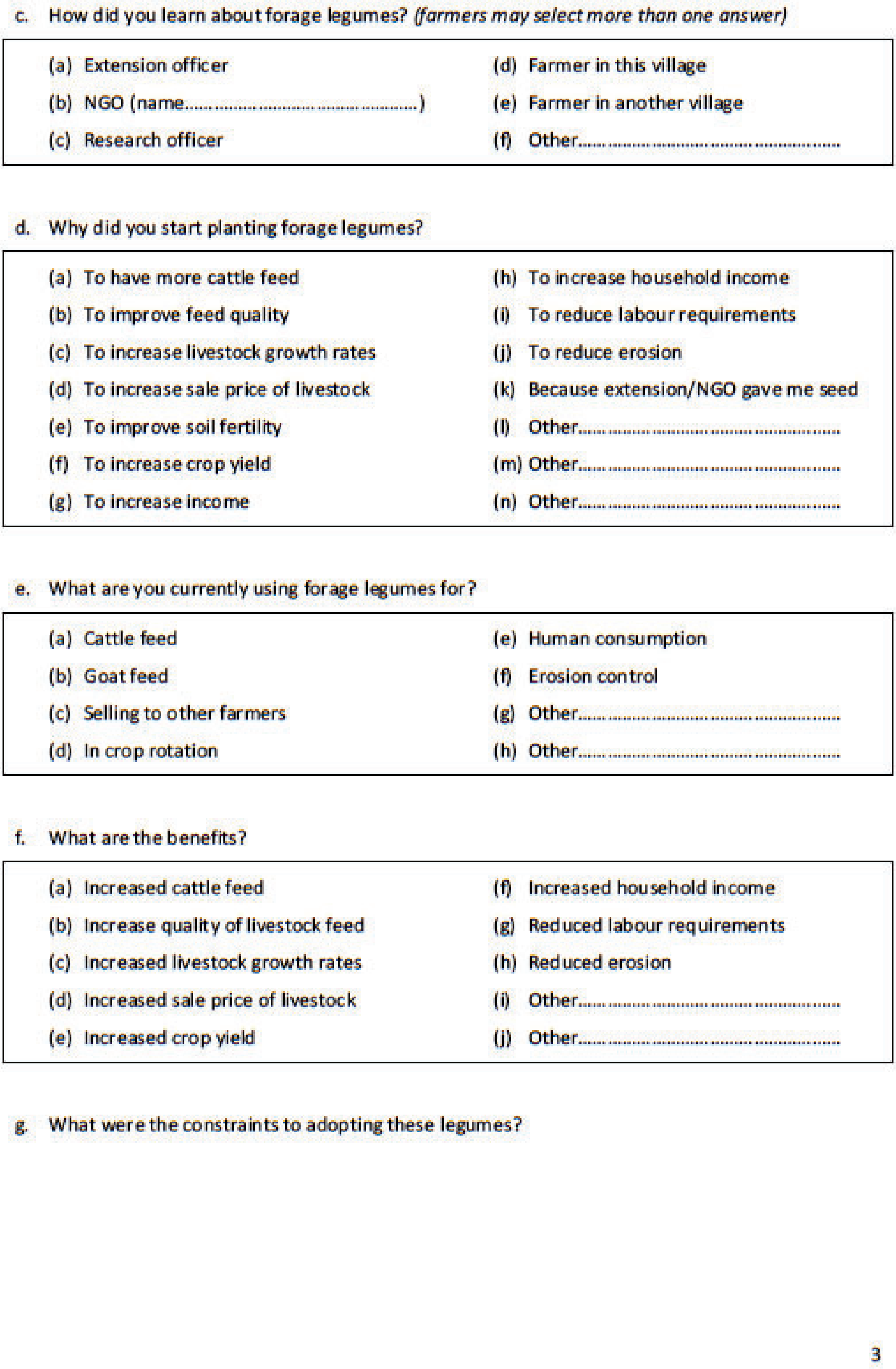
(a)	Clitoria	(d)	Siratro
(b)	Centrosema	(e)	Other …………………………………………………
(c)	Lablab	(f)	Other …………………………………………………

a. What area is planted? (are)

(a)	0 – 0.5 are	(d)	2.1 – 3 are
(b)	0.6 – 1 are	(e)	3.1 -5 are
(c)	1.1 – 2 are	(f)	> 5 are

b. Are the forage legumes planted with trees/crops?

(a) Yes (b) No	If yes what trees/crops?	
	(a) Maize	(c) Leucaena
	(b) Rice	(d) Other…………………………………



c. How did you learn about forage legumes? *(farmers may select more than one answer)*

(a) Extension officer
(b) NGO (name..)
(c) Research officer
(d) Farmer in this village
(e) Farmer in another village
(f) Other..

d. Why did you start planting forage legumes?

(a) To have more cattle feed
(b) To improve feed quality
(c) To increase livestock growth rates
(d) To increase sale price of livestock
(e) To improve soil fertility
(f) To increase crop yield
(g) To increase income
(h) To increase household income
(i) To reduce labour requirements
(j) To reduce erosion
(k) Because extension/NGO gave me seed
(l) Other..
(m) Other..
(n) Other..

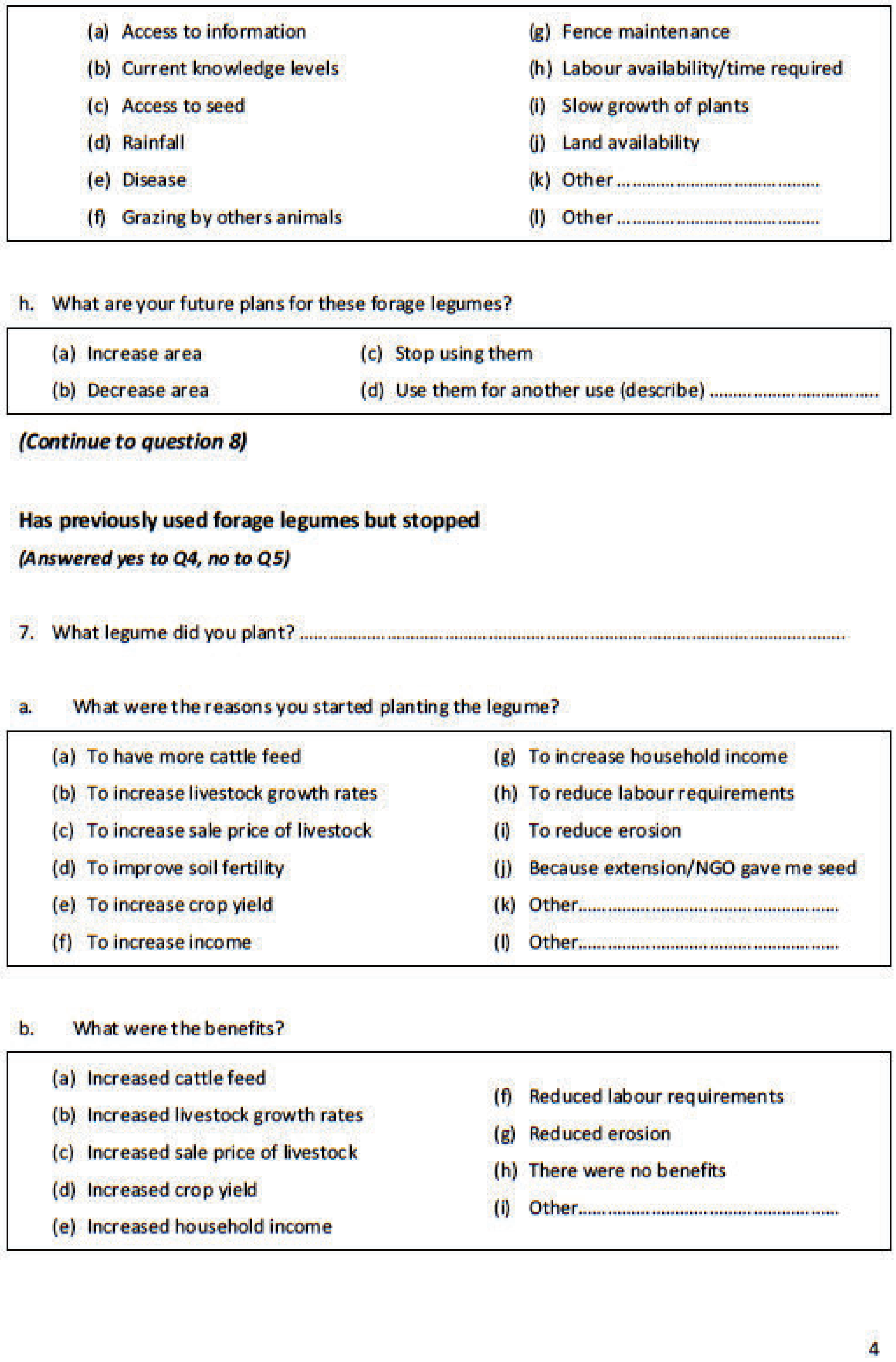
e. What are you currently using forage legumes for?

(a) Cattle feed
(b) Goat feed
(c) Selling to other farmers
(d) In crop rotation
(e) Human consumption
(f) Erosion control
(g) Other..
(h) Other..

f. What are the benefits?

(a) Increased cattle feed
(b) Increase quality of livestock feed
(c) Increased livestock growth rates
(d) Increased sale price of livestock
(e) Increased crop yield
(f) Increased household income
(g) Reduced labour requirements
(h) Reduced erosion
(i) Other..
(j) Other..

g. What were the constraints to adopting these legumes?



(a) Access to information
(b) Current knowledge levels
(c) Access to seed
(d) Rainfall
(e) Disease
(f) Grazing by others animals
(g) Fence maintenance
(h) Labour availability/time required
(i) Slow growth of plants
(j) Land availability
(k) Other ……………………………………
(l) Other ……………………………………

h. What are your future plans for these forage legumes?

(a) Increase area
(b) Decrease area
(c) Stop using them
(d) Use them for another use (describe) ………………………………

(Continue to question 8)

Has previously used forage legumes but stopped

(Answered yes to Q4, no to Q5)

7. What legume did you plant? ……………………………………………………………………………………

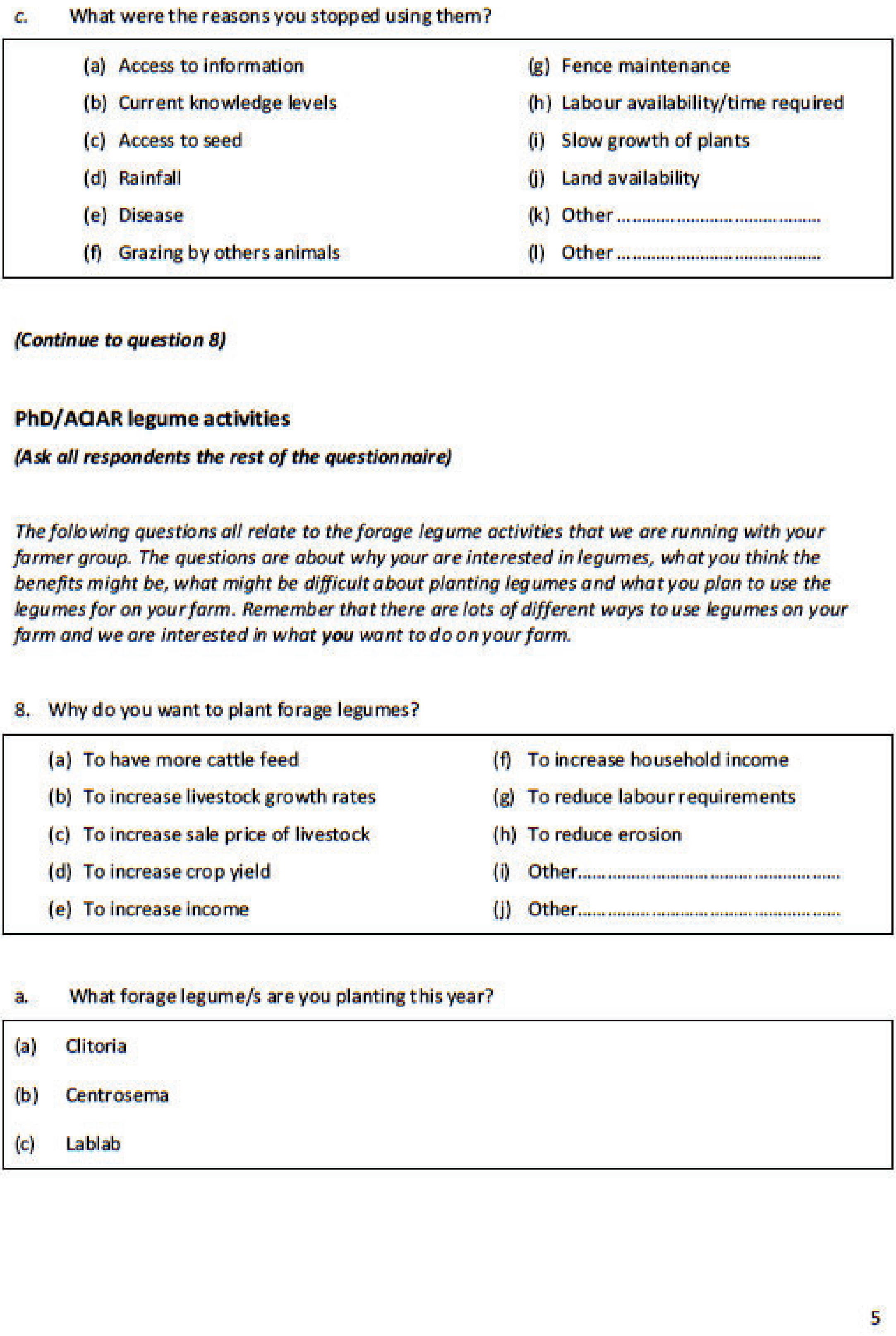
a. What were the reasons you started planting the legume?

(a) To have more cattle feed
(b) To increase livestock growth rates
(c) To increase sale price of livestock
(d) To improve soil fertility
(e) To increase crop yield
(f) To increase income
(g) To increase household income
(h) To reduce labour requirements
(i) To reduce erosion
(j) Because extension/NGO gave me seed
(k) Other……………………………………………
(l) Other……………………………………………

b. What were the benefits?

(a) Increased cattle feed
(b) Increased livestock growth rates
(c) Increased sale price of livestock
(d) Increased crop yield
(e) Increased household income
(f) Reduced labour requirements
(g) Reduced erosion
(h) There were no benefits
(i) Other……………………………………………

4



c. What were the reasons you stopped using them?

(a) Access to information
(b) Current knowledge levels
(c) Access to seed
(d) Rainfall
(e) Disease
(f) Grazing by others animals
(g) Fence maintenance
(h) Labour availability/time required
(i) Slow growth of plants
(j) Land availability
(k) Other …………………………………
(l) Other …………………………………

(Continue to question 8)

PhD/ACIAR legume activities

(Ask all respondents the rest of the questionnaire)

*The following questions all relate to the forage legume activities that we are running with your farmer group. The questions are about why your are interested in legumes, what you think the benefits might be, what might be difficult about planting legumes and what you plan to use the legumes for on your farm. Remember that there are lots of different ways to use legumes on your farm and we are interested in what **you** want to do on your farm.*

8. Why do you want to plant forage legumes?

(a) To have more cattle feed
(b) To increase livestock growth rates
(c) To increase sale price of livestock
(d) To increase crop yield
(e) To increase income
(f) To increase household income
(g) To reduce labour requirements
(h) To reduce erosion
(i) Other……………………………………………
(j) Other……………………………………………

a. What forage legume/s are you planting this year?

(a) Clitoria
(b) Centrosema
(c) Lablab

b. Some types of legumes have different characteristics to other legumes, why did you choose this/these species?

(a) It will regrow after cutting	(e) It looked like it would be good livestock feed
(b) Seed is easy to harvest	(f) You can eat the seeds
(c) It looks like it will grow well	(g) To help control erosion
(d) I had heard about/seen that legume before	(h) Other..

c. Where are you planting the forage legumes? ....

d. What area of land do you have prepared to plant the legumes? (are)

(a)	0 – 0.5 are	(d)	2.1 – 3 are
(b)	0.6 – 1 are	(e)	3.1 -5 are
(c)	1.1 – 2 are	(f)	> 5 are

e. Are you planting the legumes with any other crops/trees?

(a) Yes (c) No	If yes what trees/crops?	
	(a) Maize	(c) Leucaena
	(b) Rice	(d) Other..

f. Who in the household is making the decisions about where to plant and how to manage the legumes?

(a) Man only	(c) Man and women together
(b) Woman only	(d) Other. ....

g. Who in the household will provide the labour to plant and manage the legumes?

Activity	Man	Women	Teen (13-19)	Children (<13)	Elderly (>65)
Prepare land					
Plant					
Management (i.e.weeding)					
Feeding to livestock					

Perceptions and opinions about forage legumes

9. What do you understand to be the benefits of forage legumes?

(1) High livestock feed quality
(2) Increase livestock growth
(3) Increase sale price of livestock
(4) Increase household income
(5) Improve soil fertility
(6) Increase crop yield
(7) Reduce labour requirements
(8) Reduce erosion
(9) Other……………………………………
(10) Other…………………………………….

10. *The next set of questions is asking you about your awareness and confidence using forage legumes. Make sure that when you answer the questions you are thinking about forage legumes only and not about tree legumes or other forages.*

In your opinion, what is:

a. Your awareness of the benefits of forage legumes?

1	2	3	4	5
No awareness	Low	Medium	High	Very high

b. Your confidence in using forage legumes?

1	2	3	4	5
No confidence	Low	Medium	High	Very high

c. Your current knowledge about how to grow and utilise forage legumes?

1	2	3	4	5
No knowledge	Low	Medium	High	Very high

d. Your access to information on growing and utilising legumes?

1	2	3	4	5
No access	Low	Medium	High	Very high

11. What do you consider to be the key constraints for growing and using forage legumes?

(a) Access to information
(b) Current knowledge levels
(c) Access to seed
(d) Rainfall
(e) Disease
(f) Grazing by others animals
(g) Fence maintenance
(h) Labour availability/time required
(i) Slow growth of plants
(j) Land availability
(k) Other ....
(l) Other ....

12. How do you see your future use of forage legumes in your farming system?

....

....

....

....

Household objectives

13. *I would now like to ask you about your household and what you are currently trying to achieve. We would like to ask you about what you would like see changed in 5 years time for you're your family or farm. These might include producing more food for your family, having your children finish secondary school, increasing your household income, increasing the number of cattle you own or there might be other more important things that you'd like to tell us about.*
    a. Could you now please tell us what you are currently focusing on trying to achieve for your family and farm?

    ....

    ....

    ....

    (After this discussion ask the following question)

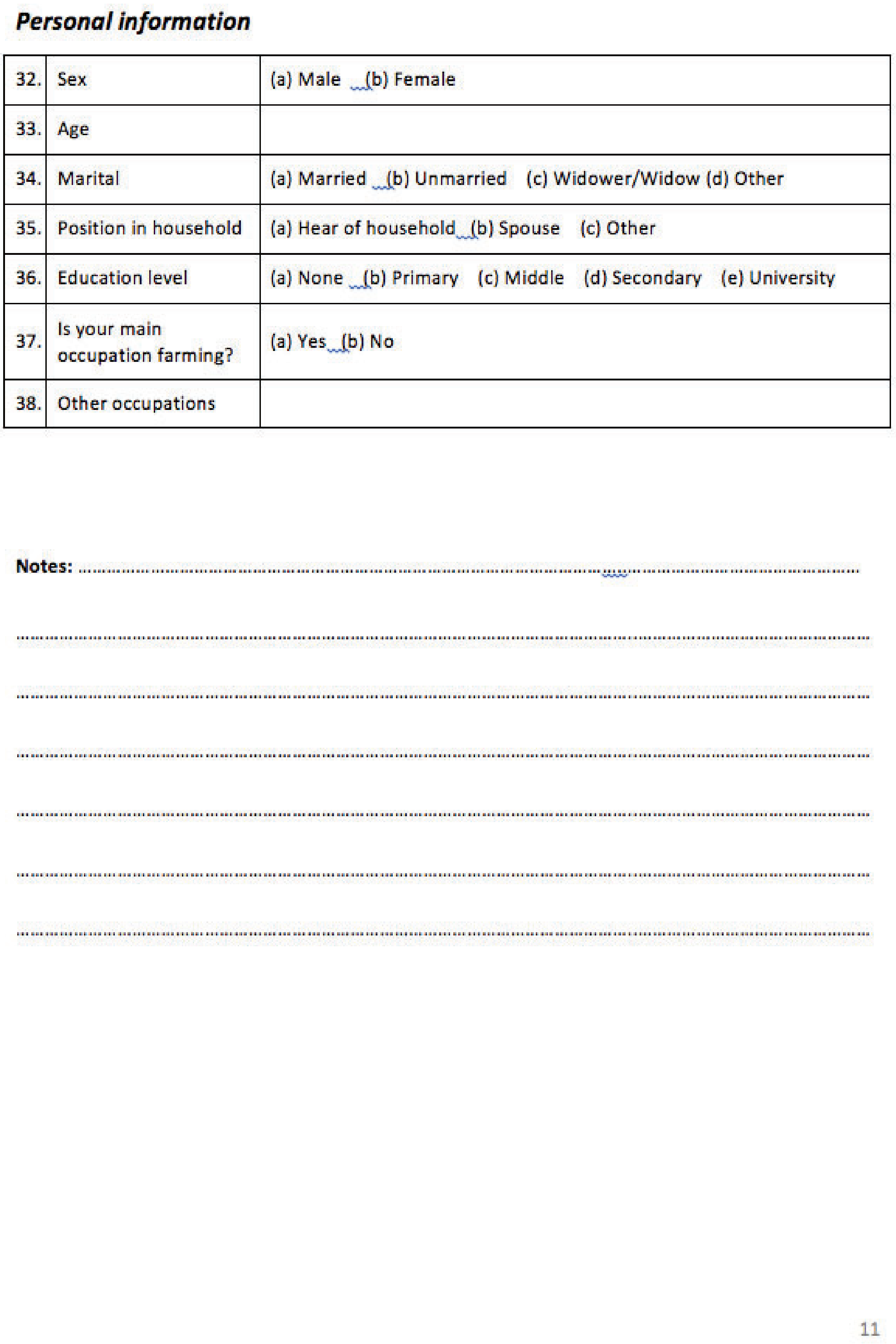
    b. Of the things we've just discussed could you list in order the three most important things you would like to see changed in 5 years time?

	Objective	Rank (1 – 3, 1=most important)
a.	Produce enough food	
c.	Provide children's education	
b.	Maximise total household profit	
d.	Maximise the number of livestock the household owns	
e.	Maximise the number of livestock sold every year	
f.	Other…………………………………………	
g.	Other…………………………………………	

Farm information

This question is about your farm, how much land you own and how many livestock you own. Please remember that your name will remain confidential so that when we use this information no one will know that it is about your farm and family.

14.	What area of dryland do you own? (are)	
15.	What area of wetland do you own? (are)	
16.	What area of maize did you plant this year? (are)	
17.	What area of rice did you plant this year? (are)	
18.	What area of dryland do you rent/have access to that you don't own? (are)	
19.	What area of wetland do you rent/have access to that you don't own? (are)	
20.	How many cattle do you own?	
21.	How many cattle do you contract fatten?	
22.	How many goats do you own?	
23.	How often do you harvest enough maize to feed your family?	(a) Every year (b) Most years (c) Half the time (d) Never
24.	How many adults (20-65) are there in your household?	
25.	How many days/hours a week do adults (20-65) work on the farm?	
26.	How many teenagers (13-19) are there in your household?	
27.	How many days/hours a week do teenagers (13-19) work on the farm?	
28.	How many children (<13) are there in your household?	
29.	How many days/hours a week do children (<13) work on the farm?	
30.	How many elderly (>65) people are there in your household?	
31.	How many days/hours a weed do elderly (>65) people work on the farm?	



Personal information

32.	Sex	(a) Male (b) Female
33.	Age	
34.	Marital	(a) Married (b) Unmarried (c) Widower/Widow (d) Other
35.	Position in household	(a) Hear of household (b) Spouse (c) Other
36.	Education level	(a) None (b) Primary (c) Middle (d) Secondary (e) University
37.	Is your main occupation farming?	(a) Yes (b) No
38.	Other occupations	

Notes: ……………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

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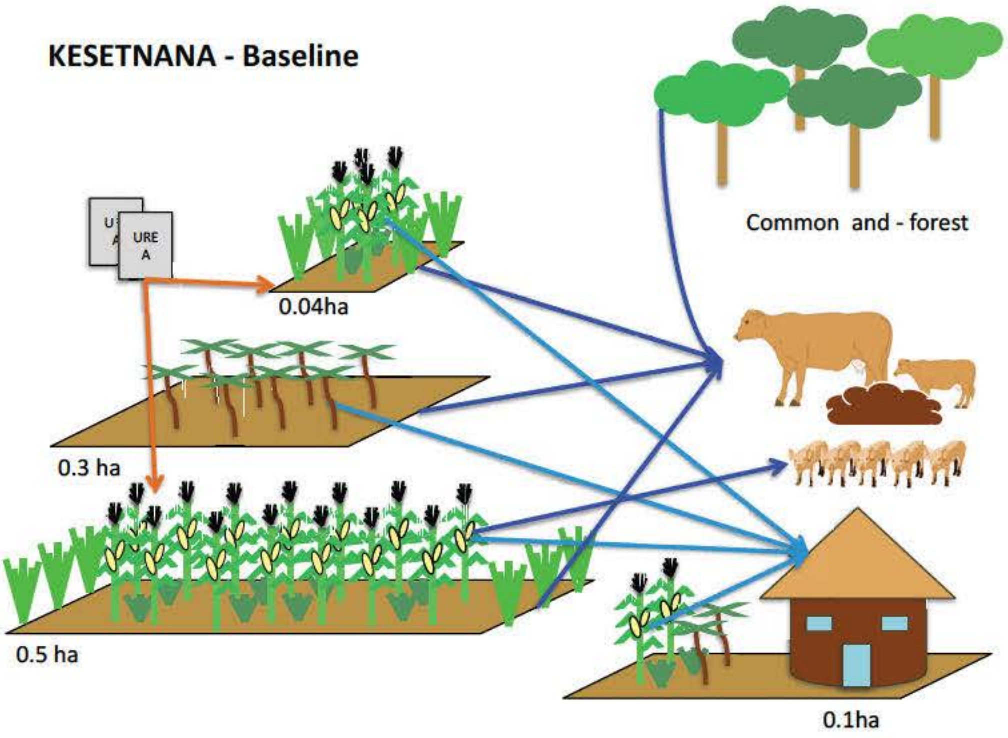
Appendix 3 Resource flow diagrams

KESETNANA - Baseline



Oenay - Baseline

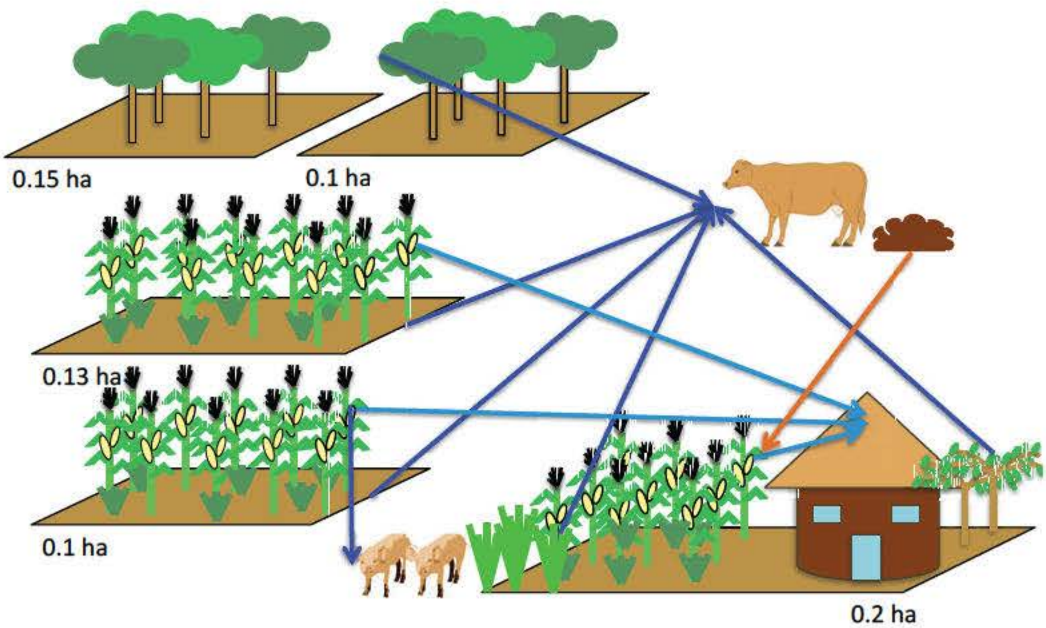


Figure 1. Stylised resource flow diagrams for case study farms at Kesetnana and Oenai, dark blue lines represent fodder allocation, light blue lines represent grain allocation and orange line represent inputs

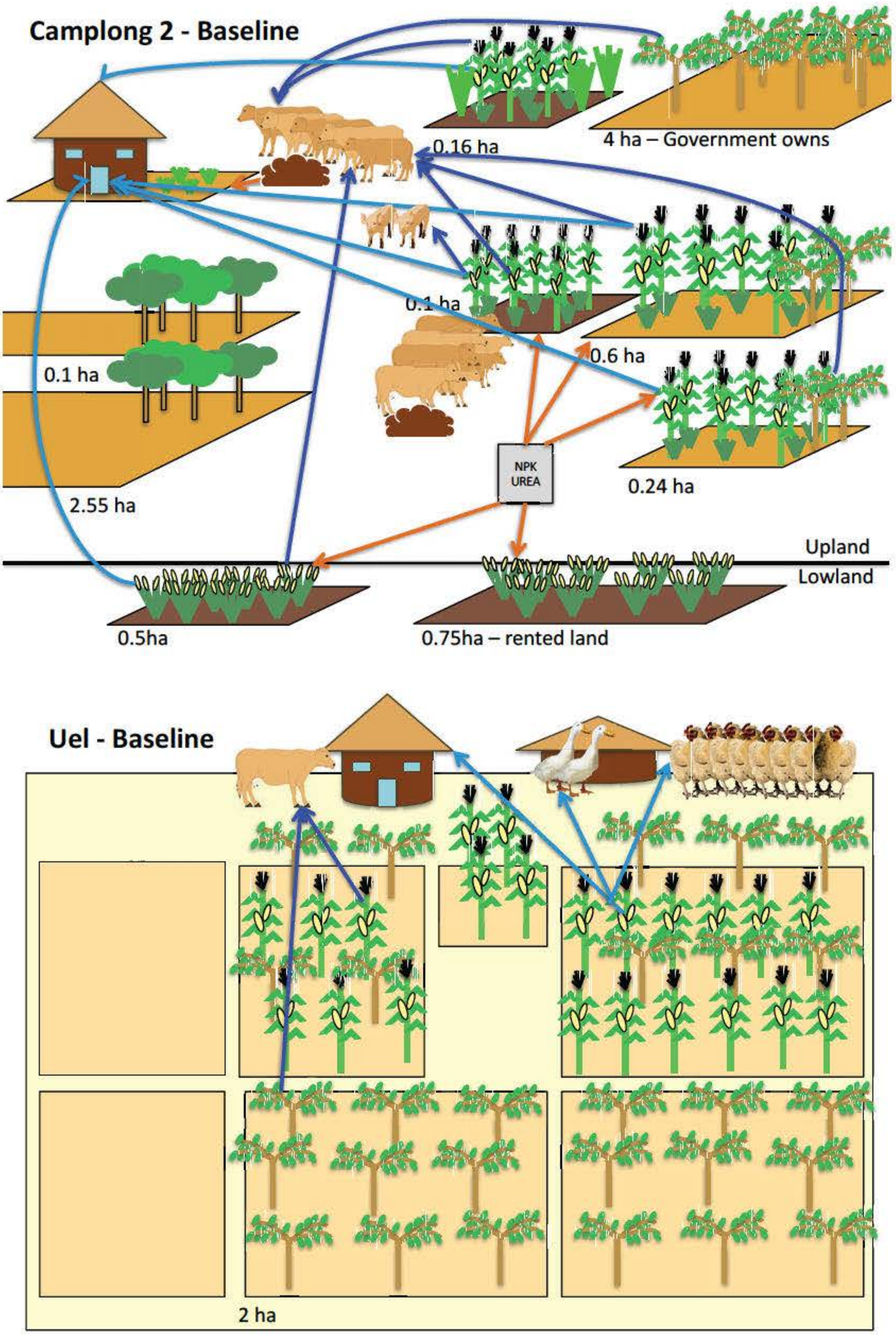


Figure 2. Stylised resource flow diagrams for case study farms at Camplong and Uel, dark blue lines represent fodder allocation, light blue lines represent grain allocation and orange line represent inputs

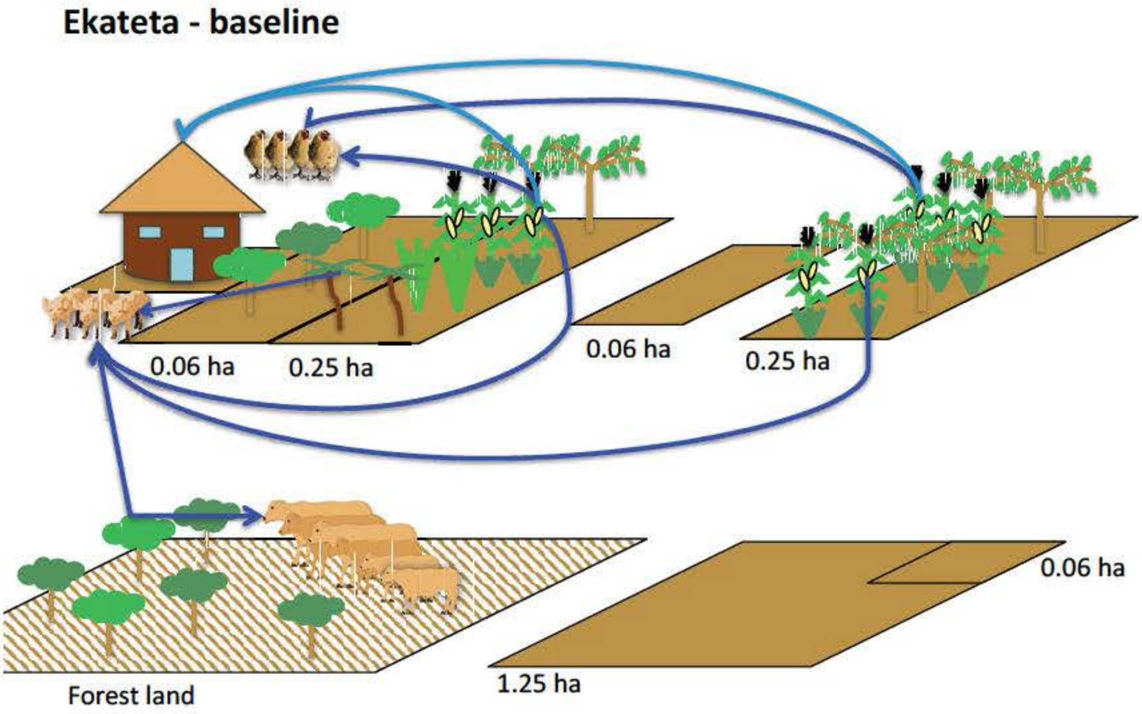


Figure 3. Stylised resource flow diagram for the case study farm at Ekateta, dark blue lines represent fodder allocation, light blue lines represent grain allocation and orange line represent inputs

Appendix 4 Causal diagram

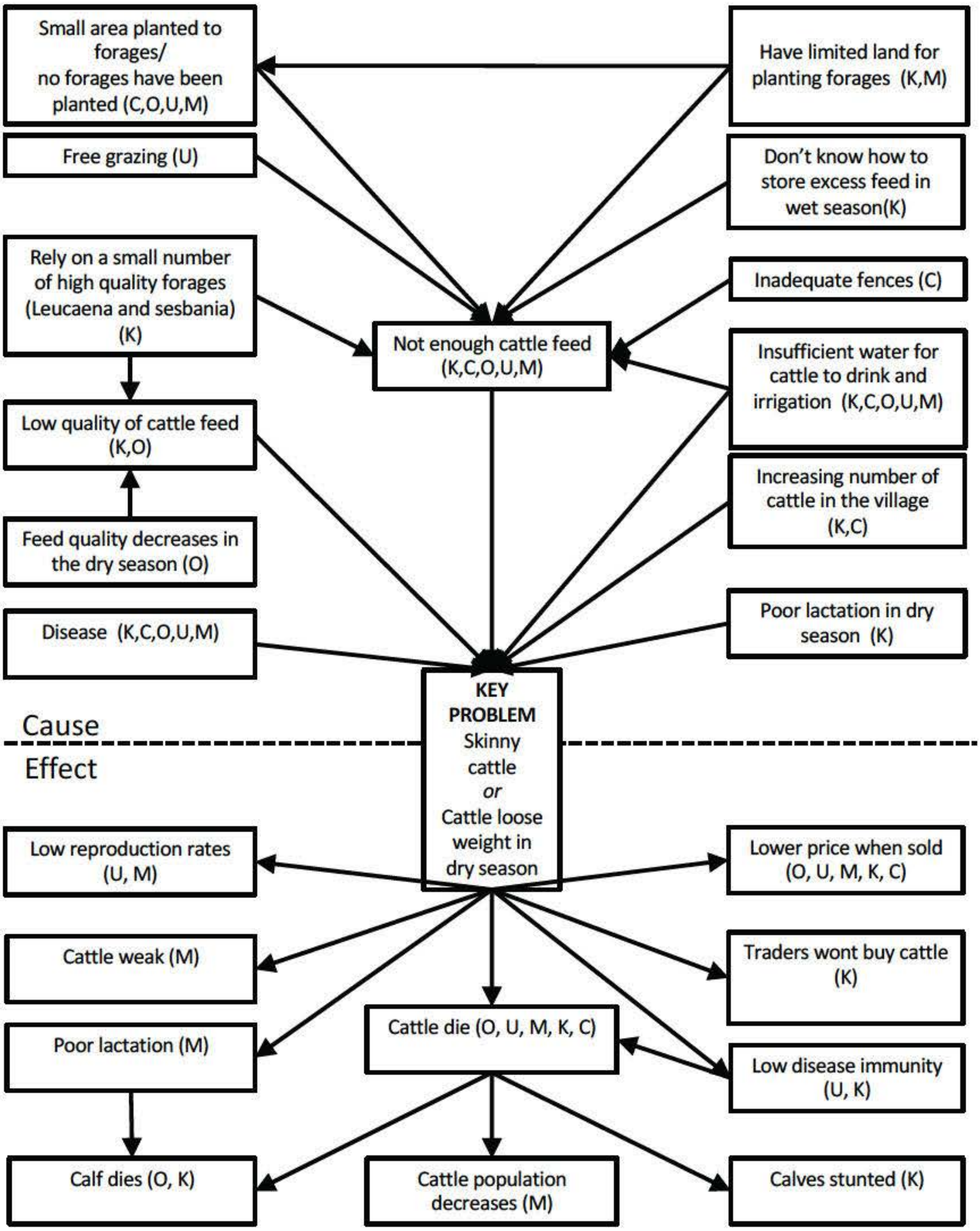


Figure 1. Stylised causal diagram for focus groups with five farmer groups at Uel (U), Manulai (M), Camplong (C), Kesetnana (K) and Oenai (O).

Appendix 5 Seasonal calendar

OENAY / BULAN	10	11	12	1	2	3	4	5	6	7	8	9
HUJAN	0	0	9	8	10	7	8	4	3	2	1	0
Jagung / ubi kayu	[illegible]	SAMA	bibit ubi kayu.		SAMA	[illegible] Tapa sedikit.	[illegible]	Hujan [illegible] Tanam ubi Jalar		sama	Ulah bln 11-12	sama
Lahan 2-5 / tanah 10	3 / 10	4 / 10	5 / 10	5 / 10	5 / 10	5 / 10	5 / 10	5 are / 1ha (10 are) 2-5 are	1 / 10	1 / 10	1 / 10	3 / 10
PAKAN	0	0	0	2	10	10	10	10	10	9	8	4
Berat Sapi		← SAMA	SAMA	GEMUK PELAN²	↑	↑	↑	↑			↓	↓
Cara pelihara sapi	Ikat =	Ikat =	Ikat =	Ikat =	SAMA [illegible]	Ikat berpindah	sama	sama	sama	sama	IKAT =	IKAT =
Waktu cari pakan (jam)	4	4	4	4	—	—	—	—	—	—	4	4

Figure 1. Example seasonal calendar developed by farmers at Oenai village

Appendix 6 Participatory modelling

Figure 1. Participatory analysis of IAT simulation outputs using resource flow diagrams and tokens representing money, maize and forage legumes.