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Improved legume pastures increase economic value, resilience and sustainability of crop-livestock systems

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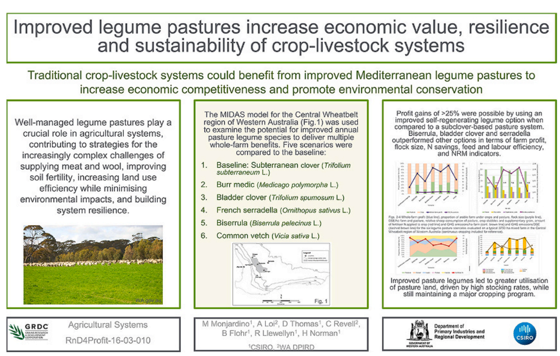
HIGHLIGHTS

- Pasture and livestock are integral to crop-dominated dryland farming systems in the Mediterranean bioclimates of Australia
- Bioeconomic modelling examined the potential for five improved annual pasture legumes to deliver multiple whole-farm benefits
- Biserrula, bladder clover and serradella outperformed in farm profit, flock size, N savings, feed/labour efficiency and NRM
- Improved pasture legumes led to greater pasture utilisation driven by stock rates while maintaining a major cropping program
- Well-managed improved legume pastures can increase economic value, resilience, and sustainability of farming systems

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Well-managed legume pastures play a crucial role in agricultural systems, contributing to strategies for the increasingly complex challenges of supplying meat and wool, improving soil fertility, increasing land use efficiency while minimising environmental impacts, and building system resilience.
OBJECTIVE: This paper examines the potential for a range of improved annual legume pasture species to deliver multiple benefits such as extending the length of the growing the season and closing feed gaps, boosting crop yields and farm profits, and contributing to natural resource management.
METHODS: Using MIDAS, a bioeconomic model of a crop-livestock farming system, we quantified the relative profitability and sustainability of five self-regenerating legume pasture scenarios – burr medic (*Medicago polymorpha* L.), bladder clover (*Trifolium spumosum* L.), French serradella (*Ornithopus sativus* L.), biserrula (*Biserrula pelecinus* L.) and common vetch (*Vicia sativa* L.) – against the baseline scenario of (mainly) subterranean clover (*Trifolium subterraneum* L.) for the medium-rainfall region of Western Australia.

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RESULTS AND CONCLUSIONS: The modelling indicated that profit gains of more than 25% were possible by using an improved self-regenerating legume option when compared to a subterranean clover-based pasture system. This could be achieved through greater utilisation of land under pastures and higher stocking rates while still maintaining a major cropping program. The whole-farm economic benefits of improved legume pastures resulted from land use adjustments to sustain more profitable cropping and livestock enterprises, and benefits were small at low stocking rates. The combination of additional feed at the start of the season and slower loss of energy values at the end of the season in the improved pasture scenarios was an important profit driver for the livestock enterprise. Other benefits included projected savings in nitrogen fertiliser for crops in rotation with the pasture, greater sheep carrying capacity, improved efficiencies in supplementary feed and labour costs per animal, lower groundwater recharge, and improved farm business resilience overall. Pastures with higher nutritional value could lead to reduced net emissions per DSE if they allow ruminants to reach finishing weight faster or improve reproductive efficiency.

SIGNIFICANCE: This whole-farm study expands previous work by comparing a broad range of annual legume pasture species developed for the soils and climatic conditions of Western Australia. The general principles behind changes in land use revealed by the MIDAS modelling have wide application beyond this Australian region, confirming the potential role of well-managed legume pastures for achieving sustainable intensification of agricultural systems, while offering sufficient flexibility for grazing systems to cope with climate variability.

1. Introduction

In the Mediterranean bioclimates of Australia, the traditional role of pasture and livestock to promote farm profitability and diversity in dryland farming systems dominated by cropping has been challenged by a combination of factors. These include effects of climate variability and/or prolonged drought (BOM, 2020; CSIRO-BOM, 2015), declining terms of trade for commodities such as wool (ABARES, 2020a), increasing complexity of mixed farming management, and the scale and intensification of cropping driven in part by significant R&D investment and innovation in crop genetics and agronomy (Kirkegaard et al., 2011). Despite favourable grain prices, intensive cropping systems are becoming more exposed to risk – especially in drier and frost-prone areas where wheat dominates (Crimp et al., 2016; Ghahramani et al., 2020) – and face ongoing sustainability issues, for example as a result of increases in herbicide resistant weeds (Owen et al., 2015; Owen et al., 2007; Walsh et al., 2007), and the rising costs of nitrogen (N) fertiliser and other inputs (Harrison et al., 2022; Kirkegaard et al., 2011).

Well-managed pastures have been promoted as a key strategy to profitably restore the sustainable balance of crop-livestock systems, such as those of southern Australia (Bell et al., 2021). Crucially, growth in productivity from livestock intensification – through improved feeding systems (i.e., extra nutrient availability), genetics and animal health – is enabled by pasture management practices designed to increase the quality and quantity of forage, such as pasture legumes, along with beneficial soil inputs and rotational grazing (Nichols et al., 2012). This is particularly relevant in Mediterranean-type environments, where the bulk of annual pasture growth occurs during late-winter and early-spring, and livestock graze dry pasture residues and crop stubbles over summer and autumn. Consequently, supply of quality feed throughout the year is uneven, prompting supplementary grain feeding to bridge the feed gap.

Industry opportunities from improved pasture species (and associated rhizobia) to generate higher profits and lower business risk for producers arise through multiple streams, including enhanced animal growth and reproduction rates, higher whole-farm stocking rates, earlier access to prime lamb markets, lower cost of supplementary feeding, and improvements in crop rotations and land conservation (Bell et al., 2014; Nicol et al., 2013; Thomas et al., 2018). In mixed systems, a phase of legume pasture also boosts crop yields through rotational benefits, such as improved soil structure and fertility as well as weed and disease breaks (Angus and Peoples, 2012; Bell and Moore, 2012; McBeath et al., 2015; Monjardino et al., 2004; Revell and Thomas, 2004), and has the potential to add value and resilience to the farm business through adjusted cost structure and diversified revenue (Bell et al., 2021; Ghahramani et al., 2020; Revell et al., 2007; Zull et al., 2017).

Nevertheless, the performance and persistence of traditional pasture legumes, such as annual subterranean clover (*Trifolium subterraneum* L.) and annual *Medicago* spp., has been poor in some areas due to a combination of reduced rainfall, soil constraints, pest and disease incursions, intensification (greater frequency) of cropping, along with the use of superseded cultivars and renovation rates limited by the high cost of pasture seed (Coventry et al., 1998; Hackney et al., 2015). Additionally, pasture species are adapted to particular climate and soil related niches, so diversity of plant and rhizobia species improves the opportunity for success at a particular location (Loi et al., 2005). Consequently, there is renewed interest in reinvigorating efforts to increase the range and scope of legumes available in pasture systems, with a focus on genetically improved and newly developed legume species enabled by innovative management methods (Ballard et al., 2019; Hackney et al., 2015; Hackney et al., 2021; Howieson et al., 2021; Loi et al., 2014; Loi et al., 2012; Nutt et al., 2021; Revell et al., 2012). In addition, their higher nutritive value benefits grazing systems (Thomas et al., 2021a) and superior N-fixing abilities (Harrison et al., 2022; Loi et al., 2022) can be exploited in consecutive years with long crop rotations to reduce the reliance on costly and less environmentally friendly synthetic nitrogen (N) without compromising the longevity of the legume seed bank (Meier et al., 2021).

Previously, the performance of these traits have been quantified for several new legume species across regions at a field plot or livestock enterprise level (Thomas et al., 2021a). In this study we evaluate the whole-farm context, which is important for producers considering new pasture options for their farm. This is because the value of pasture improvement comes not only from the additional profits generated on the land management unit on which pasture improvement occurs, but also from the opportunities generated by this improvement across the farming system (Bell et al., 2014). Previous economic evaluations in Australia's southern dryland mixed farming systems have mainly focussed on subterranean clover or medic-based pasture (Finlayson et al., 2012; Kingwell and Schilizzi, 1994; McGrath et al., 2014; Monjardino et al., 2014; Nicol et al., 2013; Thamo et al., 2017), or have considered the role of a single improved pasture legume species – on either one or multiple soil types – in addressing a specific issue such as the management of herbicide resistant weeds (Doole et al., 2009; Gibson et al., 2008a; Monjardino et al., 2004). These limitations have been partly addressed in another study comparing the performance of two new legume pasture species in a whole-farm context (Bathgate et al., 2009).

In this study we use bioeconomic modelling to evaluate a diverse range of legume species to increase pasture and livestock productivity on mixed farms and make pastures economically more attractive to farmers. For a representative crop-livestock farm in the medium-rainfall region in Western Australia, we compare the predominant regenerating legume-based pasture system with five alternative legume pasture scenarios with appropriate management packages. We specifically address two questions:

1. What is the relative contribution of improved legume pastures to a meaningful boost in whole-farm profitability, efficiency, and sustainability?
2. How much do certain biological and economic parameters need to change by (a sensitivity analysis) to improve these metrics?

By identifying specific contexts in which improved legume pastures add value and resilience to crop-livestock systems, and make the most efficient use of existing agricultural land while minimising environmental impacts, we help to define their potential role in mitigating the global pasture problem.

2. Materials and methods

2.1. Study region

The study focusses on the medium-rainfall Central Wheatbelt of Western Australia (WA) (Fig. 1). This region has a Mediterranean-type climate characterised by hot dry summers and cool wet winters. It receives a mean annual rainfall of 350 mm (BOM, 2021). The growing season for annual crops and pasture is typically from April/May until October when two-thirds of the annual rainfall occurs. The remainder of the year is characterised by low rainfall and an associated decline in the quality and quantity of feed available for livestock. Winter rainfall has become less reliable in this region, where rainfall has reached the long-term average in six winters in the last 20 years (BOM, 2021). Sheep graze dry pasture residues and crop stubbles over summer and autumn and protein and energy supplements are generally required (Thomas et al., 2021b; Young et al., 2022). The region is further characterised by soils of variable and generally low fertility, large enterprise size, a narrow range of crop options, on-farm grain storage and enterprises focussed on export markets with transport advantage to South-East Asia (Kingwell, 2011). In a typical year, pastures occupy up to half the land in low to medium rainfall areas and over two thirds of the land in high rainfall areas (Planfarm, 2019).

2.2. Pasture legume scenarios

In this study we compare the baseline (scenario 1) with five alternative annual legume species that offer potential for resilient, low-cost pasture options with appropriate management packages (scenarios 2–6). The six scenarios are listed below, with each legume species described in more detail in Appendix Table A1:

1. BASELINE: Subterranean clover (*Trifolium subterraneum* var. *subterraneum* L. cv. Dalkeith) on all soils except poor sands (French serradella)
2. Burr medic (*Medicago polymorpha* L. cv. Santiago)
3. Bladder clover (*Trifolium spumosum* L. cv. Bartolo)
4. French serradella (*Ornithopus sativus* L. cv. Margurita)
5. Biserrula (*Biserrula pelecinus* L. cv. Casbah)
6. Common vetch (*Vicia sativa* L.)

The alternative legume species have been selected for deep root systems and extended growing periods, higher biomass and nutritive value, protection from false breaks of season, appropriate patterns of hard seed breakdown, acid-tolerant rhizobia symbioses, tolerance to soil-based constraints, pests and diseases, and are aerial seeding (Ballard et al., 2019; Hackney et al., 2021; Howieson et al., 2021; Loi et al., 2005; Nutt et al., 2021).

While all pasture species used in the present study can self-regenerate each year by forming a long-lived seedbank (hardseed) that becomes germinable over time, vetch is typically sown in each year that it is required. Bladder clover is suited to a broad range of soil types, is notable for its high feed quality and grazing trials have shown it can support more grazing days per ha in a relatively dry season than subterranean clover (Norman et al., 2013). French serradella has been developed for acidic, sandy soils. The Margurita cultivar was selected from a small proportion of hard seed in the cultivar Cadiz and demonstrates a gradual release of seed dormancy over the summer period resulting in approximately 50% of the seed becoming germinable in the following year (DAFWA, 2021). Biserrula is a persistent pasture legume for Mediterranean farming systems with high levels of hard seed, a deep root system and a high level of grazing tolerance (Loi et al., 2021;

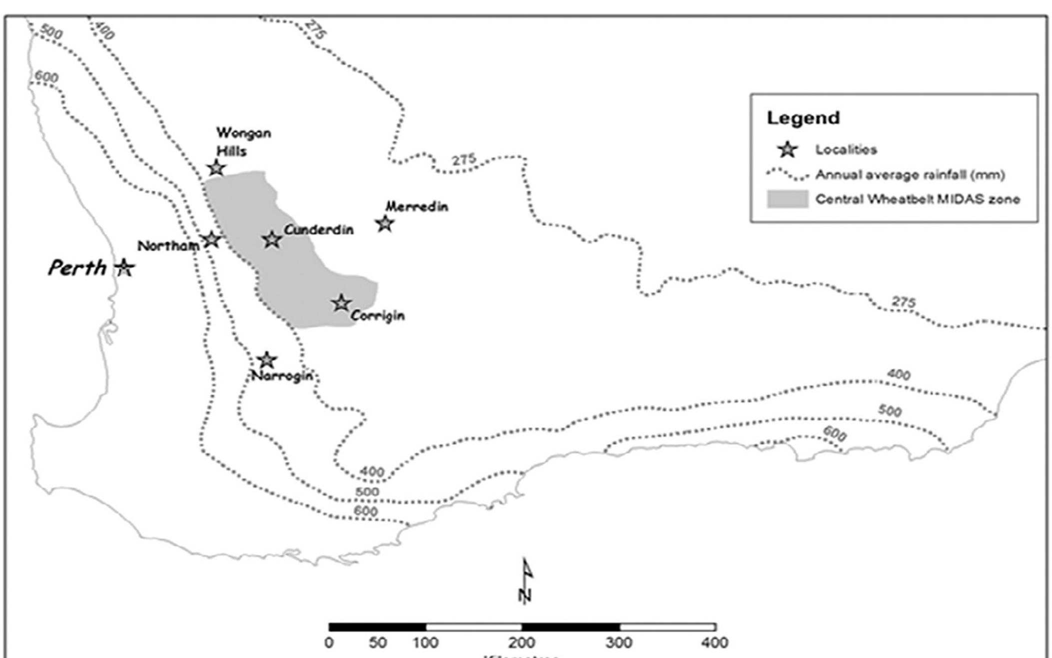

Fig. 1. The case-study region of Central Wheatbelt in Western Australia. Source: (Gibson et al., 2008b).

Thomas et al., 2015). Biserrula is suitable for use on fine textured soils with acidic and alkaline reactions including sandy loams and clay loams. It is a prolific seed producer and the seed bank can persist through multiple crop rotations (Hackney et al., 2013; Loi et al., 2001). For both serradella and biserrula, the positive effect of extra water-use at depth on next crop is possible. It is worth noting that, while species such as French serradella and biserrula are commonly grown in WA and some parts of NSW (Hackney et al., 2021; Howieson et al., 2021; Loi et al., 2005; Nichols et al., 2007; Nutt et al., 2021), subterranean clover remains Australia's most widely sown annual pasture legume, partly because its seed continues to survive under heavy grazing (Moss et al., 2021). Annual medics remain commonly utilised on the largely alkaline soils of the southern regions (Bell et al., 2014; Latta and Carter, 1996).

2.3. The MIDAS model

We employ MIDAS (Model of an Integrated Dryland Agricultural System) (Kingwell and Pannell, 1987), which uses linear programming to maximize whole-farm profit of a representative production system, subject to resource, environmental and managerial constraints. The Central Wheatbelt MIDAS version used in this study (Blennerhassett et al., 2002) has undergone extensive verification, expert assessment, recent updating of input parameters (ABARES, 2020a, 2020b), and comparison with actual farming practice via multiple applications (Bathgate et al., 2009; Bennett and Price, 2007; Byrne et al., 2010; Doole and Bathgate, 2009; Doole and Pannell, 2008; Finlayson et al., 2012; Gibson et al., 2008b; Monjardino et al., 2010; Nicol et al., 2013; Petersen et al., 2003; Robertson et al., 2010; Thamo et al., 2017; Walsh and Kingwell, 2021).

Crop-livestock farms of 3000–4000 ha make up most farm businesses in the Central Wheatbelt (Planfarm, 2019). Over several decades, livestock numbers have greatly declined in this region, although a majority of farms still have a sheep enterprise, with 50–70% of the farm area typically dedicated to crops and the remainder to pasture production for livestock grazing. Crops include cereals, grain legumes (or pulses) and oilseeds, which are grown in rotation with grass-legume-herb pastures. The length and the frequency of crop rotations are constrained by built-in yield penalties determined by limiting factors such as disease and weeds. Average farm-gate grain prices (in Australian dollars) assumed in the model include \$236/t wheat, \$234/t barley malt, \$205/t barley feed, \$470/t canola, \$246/t lupin, \$257/t field pea, \$188/t faba bean and \$282/t chickpea. Self-replacing Australian Merino sheep are the main type of livestock in the Central Wheatbelt and are raised for wool and meat (see Table 2 for prices). Farms are typically heterogeneous in terms of soil types, so up to eight land management units (LMUs, described in Appendix Table A2, including mean farm areas) can be accommodated in the current MIDAS model structure with over 80 crop-pasture sequences on each unit, along with their inter-year biological effects. The model includes 10 pasture growing periods within the year; several feeding options; a wide range of sheep categories to capture distinctive characteristics, diet requirements and management options (Young et al., 2022); several grain, stubble and wool quality classes; soil nitrogen balance and fertilization options; deferment of pasture grazing from one time period to the next accounting for a decline in quality and quantity of dry feed; groundwater recharge (based on rooting depth); machinery specifications; chemical control of diseases, pests and weeds; fixed and casual labour; and detailed farm finance enabling comparison of whole-farm profit between scenarios. The model also accounts for greenhouse gas (GHG) emissions from livestock (methane) and cropping (carbon dioxide and nitrous oxide), as measured or estimated and reported in the national inventory of emissions using methods outlined initially in the National Inventory (2011), discussed in the MIDAS context (Thamo et al., 2013), and updated recently (CleanEnergyRegulator, 2022). Key model outputs include land use, crop and livestock production measures, feed base, economic and sustainability indicators. While seasons are not explicitly described, the model can be run with a range of parameter values to assess the influence of different production levels on the profit-maximizing mix of enterprises and the level of farm profit. For example, the risk-cost of feeding grain reflects the riskiness of feeding grain in different seasons.

2.4. Modelling the pasture legume scenarios

The Central Wheatbelt MIDAS was parameterised for six pasture legume scenarios in terms of costs of establishment and maintenance; rates of initial germination, growth, decay and yearly regeneration; average proportion of legume in the sward; N content, dry matter digestibility; and biomass produced. In the present analysis each pasture option was evaluated separately because of limitations in modelling a suite of different pastures across different LMUs.

Example parameters are shown in Table 1 for a loamy sand/sandy loam (LMU 5). Parameterisation of key costs and characteristics of different pasture species was based on a wide range of sources, including research expertise, farmer survey data, electronic databases, technical reports and scientific literature (Ballard et al., 2019; Condon, 2017; Hackney et al., 2015; Hackney et al., 2021; Howieson et al., 2021; Loi et al., 2014; Loi et al., 2001; Loi et al., 2012; Loi et al., 2021; Loi et al., In review; Norman et al., 2013; Nutt, 2010; Nutt et al., 2021; Planfarm, 2019; Revell et al., 2007; Revell et al., 2012; Thomas et al., 2021a; Thomas et al., 2010b; Thomas et al., 2015).

2.5. Sensitivity analysis

A series of sensitivity analyses were conducted to test the model response to key parameters and to explore relative trade-offs and breakeven points according to the value ranges shown in Table 2.

- Proportion of initial pasture germination
- Proportion of legume in the sward
- Total pasture dry matter digestibility (DMD), increased proportionally across the season
- Commodity prices (urea fertiliser, wool, prime lamb)

The choice of parameters aimed to target crucial and highly variable economic drivers of the system, such as early pasture season growth (germination), late pasture season growth and nutritive value (DMD, % legume), stocking rate (wool and lamb prices) and N requirements (urea price).

3. Results and discussion

The contribution of the five improved legume pastures to whole-farm profitability is reported in the context of system-wide interactions and trade-offs on a mixed farm with varying soil types and multiple land use options (Table 3). Default results (i.e., using model default assumptions) for whole-farm profitability and enterprise diversity, land use and optimal rotations, livestock and feed base, fertiliser N and several natural resource management (NRM) indicators have been generated for each legume pasture scenario, assuming utilisation by the grazing flock (Table 3). A reminder that the default runs assume a standard proportion of legume in the sward mix (as specified in Table 2), with grasses and herbs making up the remainder. The pasture legume content is reflected in the DMD% and crude protein driving animal production after spring. Results of sensitivity analyses on key pasture parameters and commodity prices are presented in section 3.6.

3.1. Whole-farm profitability, efficiency and diversification

The results shown in Table 3 and Fig. 2 suggest that replacing the baseline subterranean clover with harder-seeded legume pastures has the potential to boost whole-farm profitability by an average 24% (8% serradella, 27% bladder clover and 37% biserrula). However, vetch

Table 1
Key input data used (LMU 5 loamy sand/sandy loam example) for baseline and improved pasture scenarios in Central Wheatbelt MIDAS. The seasonal growth rates for the LMU 5 example can be visualised in Appendix Fig. A1. The negligible growth rates in periods P8 – P10 are not shown.

Parameter	Growing season period (start date)	Subclover	Burr medic	Bladder clover	French serradella	Biserrula	Vetch
Pasture type/seed hardness		Self-regenerate	Self-regenerate	Self-regenerate	Self-regenerate	Self-regenerate	Sown
Years to reseed pasture[1]		4	4	4	4	6	1
Seeding rate (kg/ha)		10	10	10	6	5	20
Average cost of seed ($/kg)[2]		6	6	6	10	13	3
Establishment costs ($/ha/year)[3]		34	34	34	35	24	140
Post-establishment costs ($/ha/year)[4]		30	30	30	30	30	30
Average % of legume in sward		50	50	50	50	65	75
Average N content of legume (%)		2.0	2.2	2.5	3.2	4.5	3.5
Growth rates (kg/ha/day)	P1 (1 May)	12	12	12	10	14	10
	P2 (24 May)	8	8	8	8	8	19
	P3 (14 Jun)	22	27	24	27	27	29
	P4 (19 Jul)	38	39	41	39	41	41
	P5 (13 Sep)	28	30	34	30	34	40
	P6 (11 Oct)	5	8	8	10	12	14
	P7 (1 Nov – 22 Nov)				4	8	7
Dry matter digestibility (%)	P1 (1 May)	80	80	81	81	81	80
	P2 (24 May)	80	80	81	81	81	80
	P3 (14 Jun)	80	80	81	81	81	80
	P4 (19 Jul)	80	80	81	81	81	80
	P5 (13 Sep)	78	65	83	75	79	78
	P6 (11 Oct)	70	60	79	68	73	70
	P7 (1 Nov)	55	50	70	57	62	62
	P8 (22 Nov)	53	48	63	51	58	58
	P9 (1 Mar)	50	46	55	50	51	50
	P10 (16 Apr)	46	44	50	46	46	46
	P1 (30 Apr)	42	42	45	42	42	42
	Season average	65	61	70	65	67	66
Biomass (kg/ha)	P1 (1 May)	440	440	440	440	440	880
	P2 (24 May)	700	700	700	700	700	1183
	P3 (14 Jun)	1100	1100	1100	1100	1100	1669
	P4 (19 Jul)	2100	2100	2100	2100	2100	2736
	P5 (13 Sep)	2990	2990	2990	3125	3215	3664
	P6 (11 Oct)	3800	3584	3854	4123	4258	4393
	P7 (1 Nov)	2500	2358	2535	2890	2943	2890
	P8 (22 Nov)	1500	1415	1521	1734	1766	1734
	P9 (1 Mar)	800	755	811	925	942	925
	P10 (16 Apr)	650	613	659	751	765	751
	P1 (30 Apr)	300	283	304	347	353	347
	Season average	1535	1485	1547	1658	1689	1925

1 Assumed values are conservative (up to 10 years for the regenerating species).
2 Assumed prices reflect a stable trend over past 3–4 years for commercial seed prices.
3 Include seed and seeding, inoculum, knockdown herbicide and fertiliser (note that total establishment cost is divided by the number of years to reseed pasture).
4 Include insecticide and selective and pre-emergent herbicide.

Table 2
Selected parameters and value ranges used in sensitivity analysis.

Parameter	Default	Sensitivity range		
Initial germination *(% relative to default per LMU)*	100%	75%	50%	–
Proportion of legume in sward[1]	Standard	High	Low	–
Clovers, medics, serradella (%)	50	75	25	
Biserrula (%)	65	95	30	
Vetch (%)	75	95	60	
Dry matter digestibility (%)	100%	+5% units	−5% units	–
Price of urea ($/t) *(% change from default)*	450	225 *(−50%)*	900 *(+200%)*	1350 *(+300%)*
Price of wool (c/kg WMI[2]) *(% change from default)*	1300	1625 *(+25%)*	975 *(−25%)*	–
Price of prime lamb ($/kg DW[3]) *(% change from default)*	5.8	7.2 *(+25%)*	7.2 *(+25%)*	–

1 Value ranges for % legume set by expert consensus.
2 Western Market Indicator.
3 Dressed weight.

(higher establishment costs) and burr medic (lower overall feeding value) reduced profitability by 30% and 38%, respectively. The three best legume options – biserrula, bladder clover, serradella – if utilised, allowed the farmer to run 20–50% more sheep on the farm, specifically 5–20% more sheep on up to a 10% larger pasture area (total of 30–40% pasture), while maintaining cropping on 60–70% of farm. In particular, the extra growth season of biserrula and quality of bladder clover were sustaining higher sheep numbers and driving a large difference in profitability. It is worth noting that biserrula pasture is assumed to have 65% legume content (due to relative unpalatability), 30% higher than the other pastures with 50% legume content, which is likely to be an important factor. The impact of relative unpalatability of biserrula on voluntary intake and possible phytotoxicity risk is not considered by the model. Mixed perceptions of its potential (low) risk to animal health could however explain slower than expected adoption by farmers (Hackney et al., 2013).

Along with consistent grain sales from a relative increase in cereals replacing less profitable oilseed and pulse crops, income from livestock rose greatly from better pastures (up to 50% increase in wool and sheep sales) (Table 3). This shifts livestock: grain income ratio closer to 1: 1, thereby significantly reducing reliance on grains only and promoting farm diversification. Moreover, reductions of up to 29% (bladder clover) in supplementary feed cost per DSE (Fig. 3), up to 25% (biserrula) in N fertiliser usage and cost (Fig. 4) and up to 20% in labour costs per DSE

Table 3
Key farm indicators from MIDAS simulations of the six legume pasture scenarios evaluated on a typical 3750 ha mixed farm in the Central Wheatbelt region of Western Australia. Baseline results are shown in bold font.

	Key farm indicators	BASELINE	Burr medic	Bladder clover	French serradella	Biserrula	Vetch
Land use	Proportion of cropped land (% of farm)	**70%**	85%	60%	70%	63%	85%
	Proportion of pasture (% of farm)	**30%**	15%	40%	30%	37%	15%
Crops	Cereal (ha)	**1430**	1628	1415	1528	1459	1797
	Canola (ha)	**624**	829	443	547	444	702
	Lupin (ha)	**477**	638	399	453	444	608
	Other pulses (ha)	**94**	94	0	94	0	94
Sheep & feed	Dry sheep equivalents (DSE/farm)	**7148**	3122	10,000	8582	10,743	2491
	Stocking rate (DSE/ha of winter pasture)	**6.4**	5.6	6.7	7.6	7.7	4.5
	Pasture consumed (kg DM/DSE/year)	**250**	190	276	241	258	234
	Crop stubble (kg/DSE/year)	**103**	116	69	96	92	121
	Supplementary grain (kg/DSE/year)	**49**	96	35	54	45	49
	Risk cost of feeding grain ($/year)	**26,259**	27,759	32,683	42,799	44,539	11,283
	Risk cost of feeding grain ($/DSE/year)	**4**	9	3	5	4	5
Economics	Farm profit ($/year)	**255,739**	158,582	324,496	275,875	351,568	178,064
	Farm profit ($/ha/year)	**68**	42	87	74	94	47
	Grain sale ($/ha/year)	**297**	355	252	285	252	364
	Wool sale ($/ha/year)	**60**	27	86	72	92	22
	Sheep sale ($/ha/year)	**84**	38	122	101	131	30
	Fertiliser costs ($/ha/year)	**63**	72	56	59	53	75
	Labour costs ($/ha/year)	**39**	31	44	42	46	30
	Labour costs ($/DSE/year)	**20**	38	17	18	16	45
Sustainability	Fertiliser N applied (kg N/ha/year)	**27**	34	22	25	20	35
	GHG emissions (kg CO_2-eq/ha/year)	**662**	402	868	785	906	341
	GHG emissions (kg CO2-eq/DSE/year)	**347**	483	326	343	316	513
	Groundwater recharge (mm/ha/year)	**20**	20	20	15	15	20

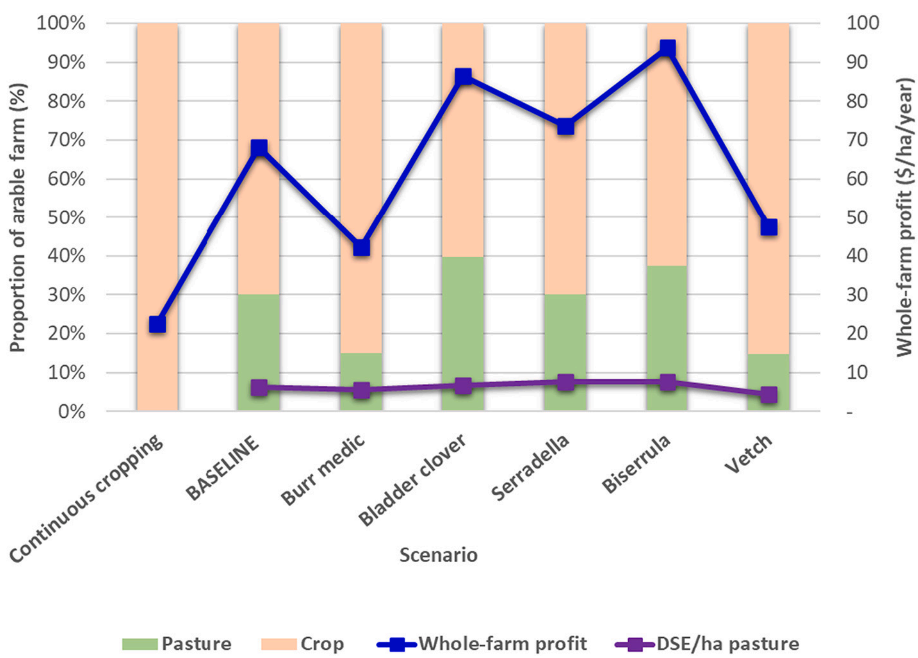

Fig. 2. Whole-farm profit ($/ha/yr) (blue line) and proportion (%) of arable farm under crop (orange bars) and pasture (green bars) for the six legume pasture scenarios evaluated on a typical 3750 ha mixed farm in the Central Wheatbelt region of Western Australia (continuous cropping included for reference). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(biserrula) contributed to profitability and efficiency gains, despite higher total feed and labour costs associated with a larger flock on the farm (Table 3). Likewise, the increase in the risk cost of feeding grain reflects the higher financial impact of feeding more sheep in different seasons; however, the riskiness of feed per DSE is similar across most scenarios (except burr medic) (Table 3).

As shown in Table 3 and Fig. 4, up to 48% of the cropping was cereals, up to 22% canola, up to 17% lupin and up to 2.5% other pulses across all the improved legume scenarios (compared to 38% cereal, 17% canola, 13% lupins and 2.5% other pulses in the baseline). These results strongly support industry recommendations for adoption of improved legume pastures in Western Australian dryland mixed systems (DAFWA, 2010, 2021). As a reference, the whole-farm profit of this system in a continuous cropping situation (i.e., pasture turned off in the default run, and no livestock) would be $84,085, or 67% lower relative to the baseline result – which in turn is consistent with per farm averages for rainfall decile 5–6 (average season) (ABARES, 2020b) – with an optimal cropping program of 50% cereals, 20% lupins, 23% canola and 6% other pulses. This result highlights the valuable contribution that pasture and livestock enterprises make to whole-farm productivity and profitability,

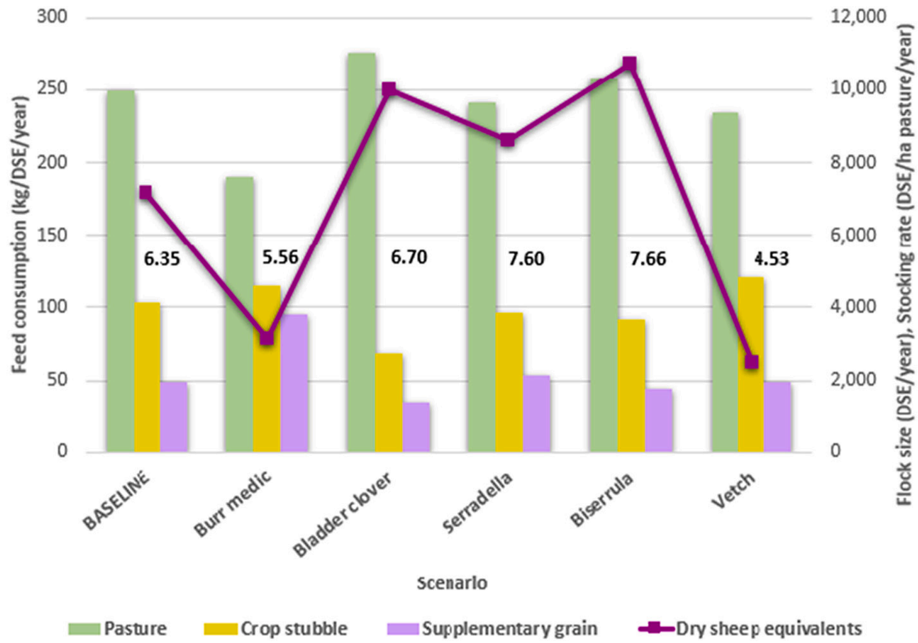

Fig. 3. Flock size (purple line), stocking rate (DSE/ha) per winter pasture area (numbers), and relative sheep consumption (kg/DSE/yr) of pasture (green bars), crop stubble (yellow bars) and supplementary grain (purple bars) for the six legume pasture scenarios evaluated on a typical 3750 ha mixed farm in the Central Wheatbelt region of Western Australia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

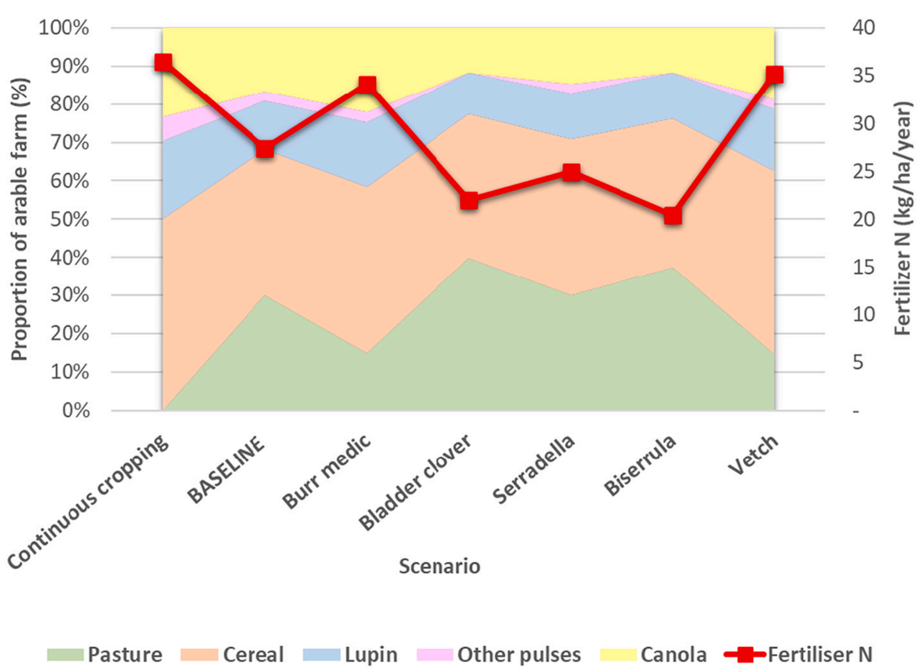

Fig. 4. Proportion (%) of arable farm area under pasture (green area) and each crop type (cereal–orange, lupin–blue, other pulses–pink and canola–yellow areas), and amount of fertiliser N (kg/ha/yr) applied to crop (red line) for the six legume pasture scenarios evaluated on a typical 3750 ha mixed farm in the Central Wheatbelt region of Western Australia (continuous cropping included for reference). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as well as the importance of matching land use and enterprise diversity to soil type suitability at the farm level (section 3.2). However, despite the high relative profitability represented here, many farms continue to choose livestock-free farming systems in the region. This is attributable to factors such as the complexity of mixed farming management in an increasingly labour-constrained farming environment. In some cases, high capital investment in cropping machinery relative to declining infrastructure for efficient livestock management has meant that cost-effectively switching to livestock or increasing livestock stocking rates to the profit-maximizing levels assumed in MIDAS is not readily achievable. The MIDAS assumptions used here include almost no switching costs or labour/skill constraints compared to those experienced by many of the cropping-oriented farms in the region.

3.2. Optimal crop rotations

Table 4 shows the area of optimal rotations by LMU for each pasture scenario. All rotations with improved pasture are highlighted (in bold font), indicating that bladder clover and biserrula were profitable on heavy sandy loam (LMUs 6 and 7) and some bladder clover-based pastures were selected on the deep duplex soil (LMU 8). Like the baseline, serradella was profitable on LMUs 1, 4, 5 and 7, while vetch and burr

Table 4
MIDAS results for area of optimal crop-pasture rotations by land management unit (LMU) for the six legume pasture scenarios evaluated on a typical 3750 ha mixed farm in the Central Wheatbelt region of Western Australia (continuous cropping included for reference). All rotations that include an improved pasture phase are highlighted in bold font.

	LMU 1	LMU 2	LMU 3	LMU 4	LMU 5	LMU 6	LMU 7	LMU 8
Cont. cropping	WLD (260)	WNWLD 400)	WNWL (614) WNWLD (36)	WNDWLD (400)	WNDWLD (375)	NWBF (375)	NWBF (565)	NWWLD (725)
Baseline	PPPP (260)	WNWL (400)	WNWL (650)	PPPPNW (266) WNDWLD (134)	PPPW (375)	NWBF (375)	PPPW (565)	NWWL (725)
Burr medic	**PPPP (260)**	WNWL (400)	WNWL (650)	WNDWLD (400)	WNDWLD (375)	NWBF (375)	3PWNDWB (294) **PPPW (271)**	NWWL (725)
Bladder clover	**PPPP (260)**	WNWL (400)	WNWL (650)	**PPW (400)**	**PPW (375)**	**PPW (375)**	**PPW (565)**	NWWL (548) **PPNW (177)**
French serradella	**PPPP (260)**	WNWL (288) **PPW (112)**	WNWL (650)	**PPW (251)** WNDWLD (149)	**PPW (375)**	NWBF (375)	**PPW (565)**	NWWL (725)
Biserrula	**PPPP (260)**	WNWL (400)	WNWL (650)	**PPW (400)**	**PPW (375)**	**PPW (375)**	**PPW (565)**	NWWL (725)
Vetch	**POPO (260)**	WNWL (400)	WNWL (650)	WNDWLD (281) **PWPW (119)**	WNDWLD (375)	NWBF (375)	**PWPW (565)**	NWWLD (404) NWWL (321)

P–pasture, W–wheat, B–barley, O–oats, N–canola, L–lupin, F–field pea, D–dry sowing crop.

medic only on two or three LMUs. No or minimal change in rotation and/or area was recorded in LMUs 1–3, where continuous pasture (PPPP on LMU1) and continuous cropping (WNWL on LMUs 2 and 3) were the optimal choice across all scenarios except vetch. In contrast, replacing subterranean clover with the harder-seeded legumes allowed for more frequent wheat cropping on LMUs 4–7, based on increased soil N from improved legume phases, along with cost-savings from less inorganic fertiliser. Of note, several suboptimal rotations were very close to the optimal baseline solution, including of mixed land use. For example, NWWL, NWBL and WNWL on LMUs 2, 3 and 8, and PPPW and PPPNW on LMUs 4 and 6, all fell within \$10 of the optimum. However, the continuous pasture rotations on LMU 1 were consistently selected for profitability, with the next best rotations PPW and PPLW >\$20 difference from the optimal PPPP. The optimal and suboptimal rotations are generally in line with recent reports for the region (Lawes et al., 2021). The fact that pastures were nearly always selected in continuous rotation or with a crop phase of just one year suggests that hard seededness to extend over a cropping phase is not always important, at least for current model assumptions.

The LMUs that go to continuous (LMU 1) or predominant pasture (LMUs 4–7) in the pasture scenarios reflect their lower productive potential for cropping due to limiting factors such as poor moisture and nutrient availability, waterlogging, wind erosion, structural decline and/or salinity. At current price assumptions, producing sheep for wool and meat, along with some cropping (mostly wheat), boosted by legume pastures is a relatively more profitable proposition for farmers making better use of marginal soils. The findings align well with previous research (Bathgate et al., 2009; Revell et al., 2007) indicating that “the benefit of improved legume pasture species to industry will depend critically on which soils they are sown. Targeting improved pastures on the poor sandplain country is a sensible starting point.”

3.3. Livestock and feed base

Modelling results show that replacing subterranean clover with harder-seeded pasture legumes with higher feeding value could increase whole-farm profitability by sustaining higher livestock numbers on a relatively similar area of pasture (Table 3 and Fig. 3). Disaggregating the results, serradella, bladder clover and biserrula pastures carried 20% to 50% more livestock on a per farm basis relative to the baseline with 7148 DSE and 1.91 DSE/ha of farm. The relatively low stocking rate per farm area corresponded, however, to greater stocking rate per winter pasture area, from 6.35 DSE/ha in the baseline up to 7.66 DSE/ha in the biserrula scenario. Burr medic and vetch options resulted in an overall reduction of flock size. The positive results for long-growth pastures like biserrula align well with a study conducted throughout south-eastern Australia correlating variations in stocking rate with growing season length (Saul and Kearney, 2002).

Livestock on the new legume swards were fed up to 29% less supplementary grain per animal (Table 3 and Fig. 3), which had a positive effect on farm profitability and resource efficiency, despite higher total supplementary grain costs associated with a larger flock being a management risk consideration overall. Less crop was sown so up to 33% less stubbles were utilised in the harder-seeded scenarios (3–5) compared to the baseline. Hay production from the pasture legumes was never selected in any scenario.

3.4. Nitrogen fertiliser

Our whole-farm results reflect the benefit of improved legume phases with higher N content reducing the need for inorganic N in dryland crop-pasture systems (Harrison et al., 2022). We found that including more productive legume species, such as bladder clover, serradella and biserrula, led to a 25% reduction in the amount of N required to meet overall crop demand (Fig. 4). However, the burr medic scenario required higher N inputs in cereal and canola crops than the baseline to offset lower biomass potential in the unsuitable WA acidic soils, and thus lower N-fixing ability. Despite significantly higher N content and biomass growth, vetch was only selected tactically in short phases and on few LMUs (Table 4), hence requiring more N fertilisers than the baseline, although 4% less than continuous cropping with a higher proportion of legume crops.

Inclusion of a legume phase in the rotation is critical for supplementing the soil N supply to wheat at the time of high wheat N demand and can maintain or increase grain protein (Muschietti-Piana et al., 2020). But, for current price assumptions, adoption of improved legume pastures, excluding burr medic, led to an average 6% increase in cereals relative to the baseline at the slight expense of less profitable pulses and oilseeds.

3.5. Sustainability

The benefits for natural resource management include a more productive and sustainable use of more marginal soils – for example more pasture in LMUs 1, 2 and 4 (Table 4) – where the positive contribution of deeper-rooted, longer-growth species extends to providing groundcover and reducing soil erosion from regular and severe winds in late summer is notable, especially as wind erosion remains a major challenge to soil health in Western Australia (Thomas et al., 2018). We also modelled a small reduction in groundwater recharge for the serradella and biserrula scenarios (Table 3), underpinned by a deeper root system (Appendix Table A1). Reduced salinity from recharge under sandy soils may be an environmental gain (Fulwood, 2018).

Increasing grazing intensity leads to an overall increase in GHG emissions (Gebbels et al., 2022; Grossi et al., 2018). Due to higher livestock numbers, serradella, bladder clover and biserrula pastures potentially increased total emissions by 18–34% relative to the baseline, with lower emissions from reduced N fertiliser, urea hydrolysis and crop residues insufficient to offset higher emissions from N fixed by legumes and the larger sheep flock. However, on a per animal basis, serradella, bladder clover and biserrula pastures were responsible for a net reduction of 1–9% in GHG emissions per DSE (Fig. 5). This relates to the provision of forage with higher digestibility and energy levels. In comparison, a continuous cropping scenario would generate 62% less total emissions than the baseline (55% less from N fixed by legumes and nil from livestock), with the most emissions coming from fertiliser, urea hydrolysis, crop residues and fuel. Overall, improved feed quality results in livestock attaining market liveweight earlier, which is consistent with pasture intensification studies in Australia and elsewhere (Cardoso et al., 2016; De Haas et al., 2019; Harrison et al., 2016; Luscher et al., 2014; Ridoutt, 2021; Thomas et al., 2021b). According to Bell et al. (2021), "in the longer term, forecast increases in worldwide demand for meat, energy costs and soil resource constraints will all encourage Australian cropping farmers to maintain mixed systems."

3.6. Sensitivity analysis

We examined how profit drivers were affected by changes in the quantity (germination, % legume) and quality (digestibility, % legume) of the pasture sward, as well as in key commodity prices.

3.6.1. Pasture germination

Assuming reduced initial pasture germination in all scenarios (75% and 50% of the default run) led to sharp reductions in whole-farm profit, pasture area, and pasture stocking rate (Appendix Fig. A2). Overall, based on our assumptions, the three more productive, hard-seeded species recorded the largest changes in whole-farm profit and outperformed most other scenarios even at reduced germination. This is important in the context of high seasonal variability, where only 50% of pasture might establish successfully.

3.6.2. Proportion of legume in the sward

We changed the proportion of legume in the sward mix from the default average to the low and high levels defined in Table 2 for each scenario. As shown in Appendix Fig. A3, increasing the digestible energy of the sward through a greater legume content significantly increased whole-farm profit in all scenarios, especially for bladder clover, serradella and biserrula. It also reduced the N input requirements in most scenarios due to the extra N-fixing potential in the system. Conversely, it had little impact on predicted stocking rates in most scenarios, except a slight increase for the less productive burr medic. A higher proportion of legume in the sward maintained or increased the area of pasture, especially in default scenarios with less pasture (burr medic, vetch and serradella). In terms of whole-farm profitability, even at lower legume densities, the three best scenarios outperformed all other scenarios at the default and high proportion of legume in the sward.

3.6.3. Pasture energy value

An increase in DMD of the legume-based pasture led to higher predicted whole-farm profitability in all scenarios (Appendix Fig. A4). The sharper boost in profit resulted from higher sheep carrying capacity and lower N fertiliser, associated with an expanded pasture area in those scenarios (Appendix Fig. A4). As for germination and legume content discussed in previous sections, bladder clover, serradella and biserrula outperformed most other scenarios even at 5% lower DMD, although variation at different time periods of the growing season could affect the relative marginal value of these pastures. Overall, the sensitivity results suggest that both pasture quantity and quality are important profit drivers for the farm business, which is consistent with other research evaluating pasture quality at the enterprise level (Thomas et al., 2021a).

3.6.4. Commodity prices

We examined the impact of changes in urea, wool and prime lamb prices on whole-farm profit and optimal management (see Table 2 for price ranges). With the cost of urea expected to rise into the future, up to 3.5 times less N fertiliser would be profitably applied, while pastures

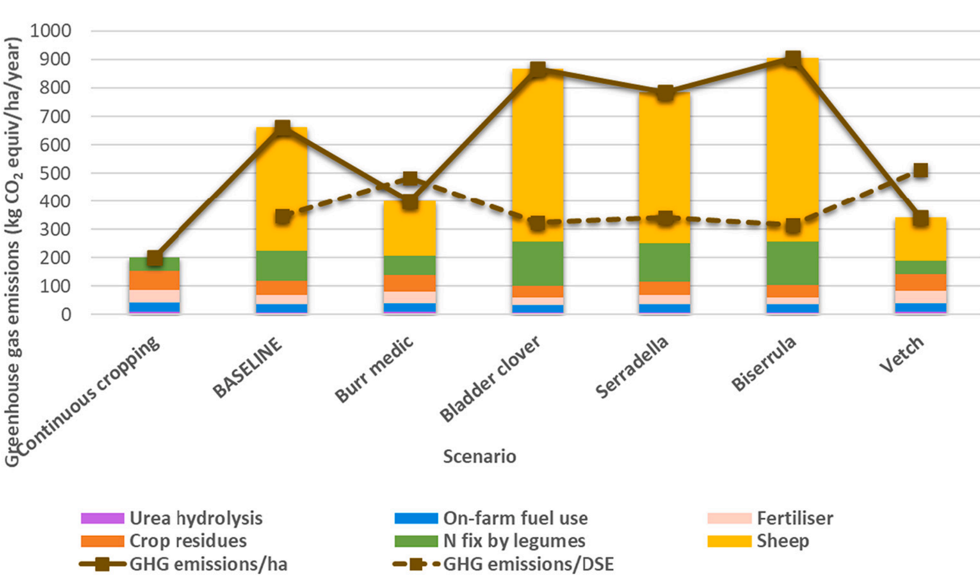

Fig. 5. Disaggregation of predicted greenhouse gas emissions (GHG) (stacked columns), GHG emissions per hectare of farm (continuous brown line) and GHG emissions per dry sheep equivalent (DSE) (dashed brown line) for the six legume pasture scenarios evaluated on a typical 3750 ha mixed farm in the Central Wheatbelt region of Western Australia (continuous cropping included for reference). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

based on bladder clover, serradella and biserrula, would still be able to maintain levels of whole-farm profitability that are higher than current subterranean clover or medic options (Appendix Fig. A5).

The inevitable decline in profit from lower wool and lamb prices – down to half of current levels – was however buffered in the three best legume scenarios, where the risk of extreme loss was clearly reduced relative to the less productive baseline, burr medic and vetch scenarios (Appendix Figs. A6 and A7). A 25% change in prices (from default 1300 c/kg wool and 5.8 $/kg DW) resulted in relatively small changes in stocking rate in most scenarios, except for burr medic with changes of up to 50%, thereby offsetting limitations associated with lower forage quality (Appendix Figs. A6 and A7). The reason is that stocking rate is driving profit, so if a farm is unable to handle large livestock numbers it will not make much more profit. In other words, the benefits of different pasture species are small at low stocking rates. This reflects reality and previous research (Thomas et al., 2021a; Thomas et al., 2019).

The optimal area of legume pasture generally increased with both higher urea prices (Appendix Fig. A5) and higher livestock prices (Appendix Figs. A6 and A7), thereby compensating for lower N supply and meeting higher demand for wool and meat.

3.7. Implications for farm management and industry recommendations

Under the assumptions in our study, the results suggest a continuing role for legume pastures in farming systems, with profit typically being greatest when growing improved legume pastures with higher energy value and/or with late-season growth. This is based on a livestock system that capitalises on the value of the extra pasture through, for example, adequate grazing utilisation and stocking rates. While subterranean clover-based pasture remains an important feed base option in the study region, the alternative species of bladder clover, serradella and biserrula produce additional feed at the start of the season (quantity), combined with slower loss of energy values at the end of the season (quality) – an attractive proposition to improve the management of mixed farming systems in southern Australia and other Mediterranean-type environments.

Crucially, our findings indicate that pasture improvement underpins whole-farm profit-maximizing decisions that lead to faster sheep growth rates, greater carrying capacity on similar areas of pasture and more cropping overall. This intensification concurs with some earlier MIDAS studies (Bathgate et al., 2009; Kingwell and Schilizzi, 1994). An exception was found for the bladder clover scenario (and to a lesser extent biserrula) where the additional sheep numbers required a shift of the optimal enterprise mix towards a greater area of improved pasture, consistent with an earlier analysis of Auld et al., 1979 and Morrison and Bathgate, 1990. Potential benefits from more efficient water use, extra biomass for conservation fodder (hay, silage) valuable in dry periods, improved soil condition, effective weed control, and improved livestock health have been reported in a pilot 2021 producer survey conducted in WA to investigate key adoption drivers of improved pasture legumes and pasture establishment techniques (Loi et al., 2021). Further explorations of complex whole-farm trade-offs in mixed crop-livestock systems, including comprehensive explanation of MIDAS outputs, can be found in recent publications e.g., Bell et al. (2021), Thamo et al. (2017) and Young et al. (2022).

Unlike common reality on most farms, the MIDAS model does not easily allow for the introduction of different pasture options in addition to the existing one. A recommended follow-up analysis could expand modelling capability to optimise the relative fit of each legume pasture when all options are present for potential selection to match soil type, depending on growth potential, farm logistics and/or market forces. Likewise, other feed options such as lucerne and forage shrubs may have a place in these landscapes (Doole and Pannell, 2008; Monjardino et al., 2014; Monjardino et al., 2010) and potentially complement annual pastures and build system resilience. Other MIDAS limitations that potentially affect the relative profitability and resilience of pasture and livestock enterprises in the broadacre farm business context include the lack of a) seasonal variation and management tactics as a steady-state model; b) risk attitude, i.e., risk-averse farmers may lower stocking rates to reduce profit variance and the risk of having periods of overstocking; and c) preference/convenience, i.e., farmers may have a preference for cropping, or choose a simple livestock management regime given time pressures (Young et al., 2022). These are critical points in our modelling context, especially given that increased stocking rates are underpinned by high levels of pasture utilisation and optimisation models may overestimate the value of pastures (Thomas et al., 2010a; Thomas et al., 2019).

Our modelling results demonstrate that incorporating improved pastures into the farming system changes the optimal sequence of crops and pastures, which has implications for pasture management and crop husbandry. There is a shift towards a greater frequency of cropping on the better cropping soils (LMU's 4–7), underpinned by the seed ecology of these improved pasture legumes that can develop long-lived seed banks that persist through the cropping phase (potentially longer than 1–2 years at higher grain prices and/or lower wool/neat prices). Importantly these pastures provide flexibility for a range of crop sequences that may occur in response to particular seasonal or enterprise market conditions, although a reliable and low-cost supply of germinable seed is a key factor in the successful adoption of improved pasture legumes (Ballard et al., 2019). Successful establishment and maintenance of a seed bank of regenerating pastures will drive down the ongoing costs of improved pasture phases in rotations, and differences in successful regeneration of legume-dominant pastures will likely vary depending on management practices, adaptation of the legumes to the soils, and hard-seed characteristics of the legume species (Nichols et al., 2007). We assume regenerating pastures are resown after four to six years (or less in these pasture-based scenarios), but this may be extended for 10–15 years under the right management with associated cost savings.

Pasture phases can rebuild soil N and soil organic carbon (SOC) reserves in the system (Nicol et al., 2013). We were able to quantify the economic value of N fertiliser savings in crop-pasture rotations with improved legumes, as also reported by Loi et al. (2022). Various improved pasture species contribute to soil N levels to greater or lesser extent depending on their overall productivity and rotational frequency, but also the degree to which they are obligate N fixers rather than N scavengers (Harrison et al., 2022). It is important, however, to monitor for potential N-mining of the soil, which in Australia is typically deficient in stable organic pools of N, because it may result in loss of soil C (Sevenster et al., 2022a; Sevenster et al., 2022b).

And while our modelling indicates reduced net emissions per DSE from improved legume pastures, this does not imply that growing more improved pastures results in a reduction of farm emissions as livestock numbers are expected to increase as well (Plevin et al., 2013). Importantly, well-managed improved legume pastures have a key role to play in developing systems that feed 10 billion people by 2050 through maximizing the efficient use of existing agricultural land while minimising environmental impacts. Further research is recommended to explore this trade-offs which have implications for farm businesses to potentially become carbon neutral (Ridoutt, 2021).

This analysis provides evidence of the relatively high potential profitability of mixed crop-livestock systems when livestock enterprises can be managed at or close to optimal levels of productivity. However, the incorporation of new pasture species may add additional (agronomic) management complexity that will initially require new knowledge and skills for implementation. This can be a barrier to adoption that needs to be overcome (Kuehne et al., 2017). It is worth noting that recent whole-farm modelling studies with emphasis on climate and financial risk in Australia cautioned against over-emphasising the merits of diversification of farm-level enterprises and urged consideration of either a livestock-only system, thereby removing cropping overhead costs, or a shift to a more crop-intensive system that lessened the unit costs of cropping overheads – along with income diversification from on-farm and off-farm sources (Ghahramani et al., 2020; Zull et al., 2017).

Evaluating the fit of improved legume pastures in a typical crop-livestock system in a Mediterranean-type environment generates evidence-based insights that can be applied to similar grazing regions of the world, particularly in parts of South America (Del Pozo and Ovalle, 2012; Ojeda et al., 2017; Oliveira Silva et al., 2017), southern Africa (Trytsman et al., 2016), and southern Europe (Hernández-Esteban et al., 2019; Pecetti et al., 2009; Perdigão et al., 2011; Sá-Sousa, 2014). For example, the Iberian *dehesas* and *montados* – traditional agro-silvo-pastoral farming systems occupying over three million hectares in southern Spain and Portugal – which are in rapid decline, could greatly benefit from improved Mediterranean legume pastures to increase economic competitiveness and promote environmental conservation (Ferraz-de-Oliveira et al., 2016; Hernández-Esteban et al., 2019; Monjardino, 1994). More broadly, we aim to explore and promote potential sustainable pathways towards reversing the decline of mixed-crop livestock systems in many parts of the world (Poffenbarger et al., 2017; Ryschawy et al., 2013) while contributing to current debates on global agricultural land use (Blaustein-Rejto et al., 2019; Ramankutty et al., 2018). We argue that well-managed improved annual legume-based grazing systems that add value, resilience and sustainability to crop-livestock systems have a key role to play in this transition.

4. Conclusion

Using bio-economic modelling we evaluated strategies for improved forage legumes to increase pasture and livestock productivity and demonstrate that improved annual legume pasture phases are a highly profitable option for mixed crop and livestock farmers. For a typical mixed farm in the medium-rainfall region in Western Australia, well-managed improved legumes had the potential to increase whole-farm profitability by up to 37% in some scenarios. The whole-farm economic benefits of improved pastures result from land usage that sustains both more profitable cropping and livestock enterprises, along with cost savings in nitrogen fertiliser, and improved soil fertility. It is worth noting that to capitalise on the improved pastures to maximize profit gain, farmers need to greatly increase stocking rate and livestock management demands and be prepared for increases in overall supplementary feed needs and labour. Crucially, this also comes with increased efficiencies on a per DSE basis, such as lower feed and labour costs per DSE, lower net emissions per DSE, as well as more productive use of land, thereby contributing to greater system resilience overall.

We highlight the need to employ a systems approach when weighing up alternative management options and competing farm objectives and decisions. In this case, representing key agro-ecological conditions, socio-economic drivers, farm resources and operations, along with enterprise trade-offs, synergies and interactions across land management units allows for a more accurate assessment of the role and value of pasture improvement in crop–livestock systems.

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Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103519.

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