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ANALYSIS

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High performance of a low input, mixed western Australian farming system: public policy implications from the case of Tolga farm

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Abstract

Tolga is a 5,200 ha sheep and cropping farm located near Kulin in Western Australia (WA). Since 2004, its production system has been a blend of conventional and alternative practices; some of these alternative practices are common in non-broadacre industries. The alternative practices are based on an understanding of soil health gained from the Australian Soil Planners system which aims to improve the farm's biological functioning and nutrient cycling.

This includes use of phase rotations with legume (subclover) pastures tended as a crop, minimal, but necessary synthetic fertilisers and chemicals, supplementary nutritional packages for pastures, animals, and soils, supplementing chemical control with nutrition and grazing management where possible, corrective liming to address soil acidity, and using deep rooted tillage radish to recycle sub soil nutrients, promote root biomass to reduce the impact of soil compaction and possibly, reduce enteric methane emissions.

Livestock performance is very high by industry standards, and crop yields, previously similar to district average, are improving in response to a greater proportion of the farm dedicated to livestock / pasture production. The reasons for the high level of livestock performance are not thoroughly understood, emphasising the need for research into the farm's system. Estimated profitability is around the median of a leading consultant's cohort of farmers for that rainfall zone; however, the low variability in its profit is reflective of the top 25% of the cohort, ranked on profit (gross margin) per hectare. The business has steadily grown over the past 30 years. Emissions (T/CO_2e/ha) are estimated to be low compared to industry benchmarks and evidence exists that the farm's total organic carbon pool is either reflective of or is as much as 40% higher than the surrounding area.

Keywords Phase farming, Nutrient cycling, Legume pasture, Sheep meat production, Soil health, Crop and pasture synergies, Farming systems, Bioeconomic modelling, Carbon emissions, Soil organic carbon

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Introduction: rationale and methodology

Rationale

This case study evolved from an economic investigation into a mixed (cropping / sheep) farming system in Western Australia's (WA) south-eastern wheatbelt. The investigation was undertaken as the system's profitability is much higher than industry norms given its higher proportion of livestock, its profit variance is much lower than those with similar profitability in comparable systems, and consequently the business has expanded to an above average size. Furthermore, its modelled emissions are significantly less than comparable mixed systems and evidence exists that its soil organic carbon (SOC) is comparable or as much as 40% more than the district average. The owners' business objective (Brendon and Gabrielle Savage, pers. com.) is sustainable intergenerational farming; sustainable refers to the resource base as well as profit. A particularly unusual production feature is evidence of high levels of livestock performance achieved by grazing in some paddocks that are dominated by older subclovers (*Trifolium subterraneum* L.) which can be highly oestrogenic, which normally constrain ewe reproduction potential [1]. This case study highlights the importance of promoting lower input mixed farming systems in WA's public policy as these innovative systems have the potential to be both profitable, more climate resilient and environmentally friendly by reducing greenhouse gas (GHG) emissions and emissions intensity and building soil carbon. They also have the potential to underpin the creation of value chains that reward low net carbon outcomes.

Methodology

The case study format was chosen as the most appropriate format to seek to explain these anomalies to the production and net emissions benefit of the WA agricultural industry [2]. The use of a combination of case study that generates detailed specific farm data from manager's records, simulation modelling and industry benchmarks can serve as a powerful tool for producers seeking low-cost, low-risk means to explore alternative scenarios for their farm systems.

Steady state bioeconomic modelling of the farm's production system was undertaken using DPIRD[1]'s EVALUS[2] bioeconomic model [3] to remove financial transaction complexity (e.g., trading across seasons) and to incorporate historical prices and seasonal conditions over a 15-year period. The EVALUS model can be used to compare different farming systems' economic and environmental performance. The simulation results were highly representative of the farm's actual financial performance. The EVALUS model incorporates production response functions (e.g., liming application, nitrogen application, nitrogen fixation legumes in rotation etc.), from the best available science. This includes the University of Melbourne's GAF emissions models, [4] drawn directly from the Australian National Inventory's functions and can account for the direct and indirect emissions from the farm gate as well as the pre-farm embedded emissions from inputs such as fertiliser and feed. Production data was provided in interview and from farm records by the owners. Analysis of meat lamb growth performance utilised lambing and abattoir slaughter records and modelling using Pastures from Space™. Observations and anecdotes are indicated through the case study. Review literature is incorporated as appropriate.

Farming system outline

Tolga farm is located near Kulin, Western Australia (WA, Fig. 1) about 300 km east-south-east of Perth. Its 5,200 arable hectares (ha) is more than 50% larger than the Medium Rainfall 4 zone (M4) average. WA's agricultural region has a typical Mediterranean climate (warm, wet winters and hot, dry summers) and the farm is in the M4 (Table 1). It has an average annual and growing season rainfall (GSR) of 350 mm and 223 mm respectively (Table 1). Tolga's management is a blend of both conventional (common to WA broadacre farming) and alternative (not common to WA broadacre farming) practices (see Table 2 for examples); some of these alternative practices are found in non-broadacre industries. Its production system is reflective of 1980's practices (cropping and pasture / livestock phases phase[3] farming), but with the adoption of new technologies.

The farm's alternative practices are based on an understanding of soil health gained from the Australian Soil Planners (ASP, [5]) system; despite the name, ASP is a whole of farm consultancy group. The ASP group also acts as a peer-to-peer learning platform with regular online meetings, ongoing online communication (via WhatsApp™), annual planning days and farm tours and on ground agronomic support. Group members collectively produce inputs needed for alternative practices, especially sourcing inputs for their liquid nutrition packages. Some of these inputs' formulations have intellectual property protection, so their composition is not discussed outside of the ASP group.

The farm's largest historical crop production risk over the seasons was deemed to be frost. This was a key driver

[1] Department of Primary Industries and Regional Development, WA.

[2] EVALUS: Economic Valuation of Alternative Land Use Sequences. This modeling capacity to examine alternative scenarios has been under development since early 2020 by DPIRD's Economic Assessment Team.

[3] Pasture and livestock phase and cropping phases with rotations within the phases (e.g., oats / clover /barley / clover etc.)

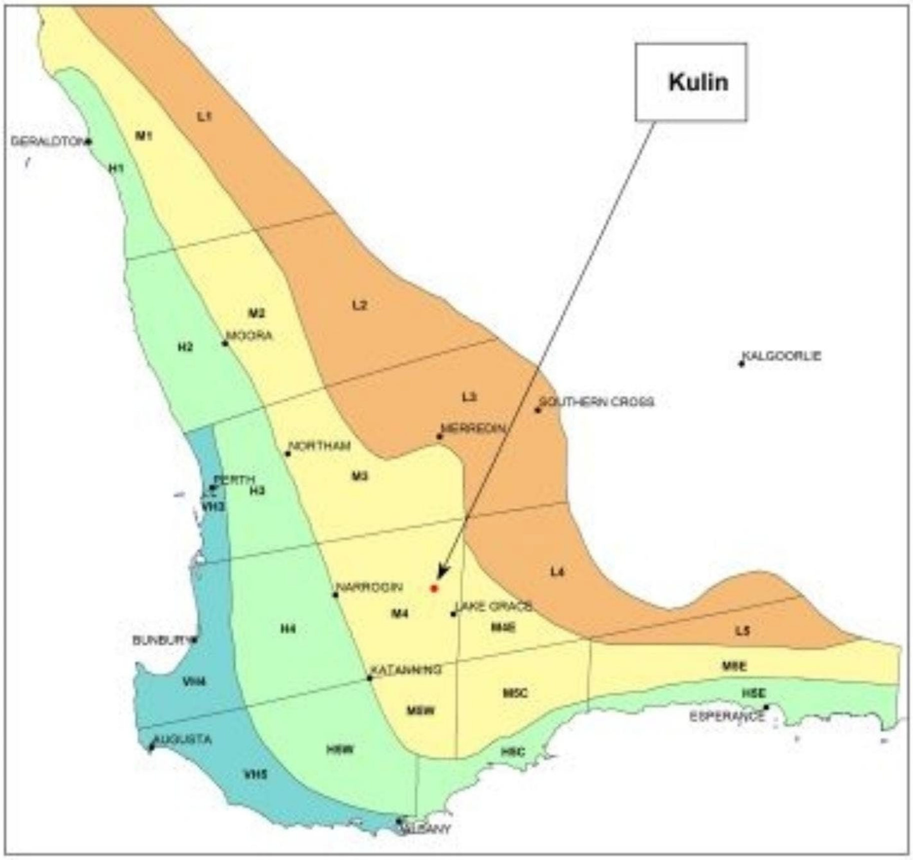


Fig. 1 Kulin in relation to WA's SW agricultural region and rainfall zones (DPIRD)
Thanks to Karen Homes, DPIRD

Table 1 Tolga Farm Summary, 2021 and Target model (from 2022)

	Nearest town	Farm size (ha)	M4 average size (ha)	Rainfall (mm)	Rainfall GSR (mm)	% Crop / Pasture	Main crops* 2021 & 2022 on	Established pasture	Stubble cover over summer
	Kulin	5,200	3,300	350	223	50:50 (2021) / 35: 65 (2022 on)	B (58%), O (38%), GW (4%) /B (40% O (60%)	Subclover (up to 90%)	1T/ha after grazing
Estimated biomass^, T/ha								3.2 (Decile 5)	
Estimated legume N, kg/ha^ EVALUS#						(2% N) 60 kg (available, 25 single rotation) 120 (available, 50 double rotation)			

*= Barley (B), Oats (O) and Grazing Wheat (GW)

^= Assessment in paddock, Dr Angelo Loi, DPIRD

#= EVALUS modelling based on DPIRD nitrogen model (***currently being updated as clearly understates available N***)

for the owners to focus on a subclover pasture dominant system (65%) and livestock. Tolga also does not produce wheat (*Triticum* aestivum L.) as it is frost susceptible, while more frost tolerant barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.) production have important synergies with its livestock pasture dominant system, especially their cereal stubbles that are utilised by sheep. It's worth noting the proportion of sheep production at Tolga is increasing, whereas the general trend in WA has been towards large scale, highly mechanised grain

Table 2 Tolga farm management practices

Conventional broadacre	Phase, liming (incorporated), synthetic fertilisers, herbicides, minimum tillage, livestock supplementary nutrition licks
Conventional but unusual	Livestock proportion, livestock genetic performance, lime application volumes, refurbished equipment, crop selection (frost and livestock synergies), livestock infrastructure, crop grazing*, reefinating
Conventional in other industries but not widely practiced in broadacre	Sap testing and foliar application (mister) especially traces and calcium (horticulture), silage (dairy), kelp (horticulture / turf / home gardening industries)
Unconventional	No insecticide sprays / only re-active fungicide applications / no chemical groups B, N and I / crimp roller** (plant control) / plant nutrition applications (cape weed & crop grazing utilisation) / tillage radish (soil compaction / observed to be a good companion to clover***) / confined feeding to reduce BCS over 2nd trimester (twin & triplet bearing composite ewes BCS 4 to 3) / SOA (in solution) + molasses to speed residue breakdown before seeding / banded liquid Ca at seeding

*https://www.publish.csiro.au/an/pdf/AN15850

**https://www.mytengineering.com.au/products/rollers/myt-crimper-roller

***Personal observation by Brendon Savage

Table 3 Tolga's crop fertiliser program

25 kg	MAP/SOP 70/30 blend *25 x.7 × 10% =* ***1.75*** *units of N / 25 x 0.7 × 21.9% = 3.83 units of P*
17 L	XFurrow* (applied with seed at seeding)
7 L	XCalibre** (liquid calcium)
7 L	Flexi N*** *42%**** x 7 =* ***2.94*** *units of N*
4.5 kg	SOP
50 g	BAC (bacillus) to promote plant growth; help with blotch. (Note, Brendon is more tolerant of some disease on his plants compared to his peers)
7 L	XSeed (seed dressing)
1 L/T	Imidacloprid (on barley seed – insecticide). Rather an insecticide is put on seed than sprayed over the paddock. This is because the barley is sown into former pasture, so it is very prone to cut worm etc.
18 kg	SOA *18 × 20.8% =* ***3.33*** *units of N* *3.33 + 2.94 + 1.75 = Total of 8.02 units of N*

SOA, Sulphate of Ammonia / SOP, Sulphate of Potash / MAP, Mono-Ammonium Phosphate

*https://www.agritrading.com.au/grosure-fertiliser-x-range

**https://www.agritrading.com.au/xcalibre

***https://csbp-fertilisers.com.au/products/liquids/liquids

****https://csbp-fertilisers.com.au/products/pasture/liquids

production, often with declining proportions of livestock [6].

Tolga's soils and plants appear sufficiently healthy to cope with its infrequent and selective chemical interventions and its comparatively low use of synthetic fertilisers (e.g., 8 kg/ha of N compared to M4 average of around 50 kg/ha. See also Tables 3 and 4). Soil health here is defined as the ability to increase the scale and rapidity of nutrient cycling as this reduces fertiliser input costs [7]. This is the principal motivation for the Savages' adoption of this approach to agriculture. The ASP approach is to stress improved soil health outcomes and not to over focus on the methodology that farmers use to achieve them. Farmers can therefore adopt the practices that best suit their circumstances and the stage of their system's development. For instance, the group especially emphasises the use of liquid calcium for root vigour (Fig. 2) which is banded[4] at seeding and applied as foliar spray (with other inputs including kelp and trace elements). Much of Tolga's nutrition inputs are applied in solution with water.

Conventional weed and pest management practices and synthetic fertilisers are used where crop production goals cannot be achieved by alternative practices. Chemicals are used strategically to solve *specific* weeds, pests and pathogen problems and are not applied as prophylactics e.g., fungicides may be used to control an outbreak of blotch[5] in a waterlogged section of a barley paddock, but it is not sprayed as a preventative measure over the entire crop.

Contiguously purchased land has been progressively integrated into the Tolga system to achieve the scale necessary for intergenerational business continuity. System integration is achieved via a renovation process of

[4] Application in a narrow band alongside the seed row.

[5] Net form (type) net blotch (*Pyrenophora teres f. teres*) and spot form (type) net blotch (*Pyrenophora teres f. maculate*).

Table 4 Annual Tolga chemical use, per hectare

Volume, ha	Name	Group	Mode of Action**
Crop			
670 gm	Glyphosate (450 g/L, knockdown, seeding)	M	Inhibitors of EPSP synthase
200 ml	Triclopyr / Garlon (knockdown, seeding)	I	Disruptors of plant cell growth (synthetic auxins)
1.25 L	Glyphosate (crop)	M	
2.2 L	Trifluralin (480 g/L, crop, May)	D	Inhibitors of microtubule assembly
280 gm	Diuron (crop, May)	C	Inhibitors of photosynthesis at photosystem II (PS II inhibitors)
120 mL	Dicamba (crop, May)	I	Disruptors of plant cell growth (synthetic auxins)
500 ml	LVE 570 (MCPA) (crop, May)	I	
600 mL	Bromoxynil (250 g/L crop, May)	C, F	Bleachers: inhibitors of carotenoid biosynthesis at the phytoene desaturase step (PDS inhibitors)
50 mL	Diflufenican (25 g/L crop, May)	F	
1 kg	Zinc		
Pasture*			
400 mL	Clethodim	A	Inhibitors of fat synthesis (ACC'ase [acetyl coA carboxylase] inhibitors)
500 mL	Paraquat	L	Inhibitors of photosynthesis at photosystem I (PSI inhibitors)

* Note, some nutrition is applied as foliar to pasture

**https://www.dpi.nsw.gov.au/biosecurity/weeds/weed-control/herbicides/herbicide-resistance

Fig. 2 Root development on vetch (*Vicia* spp), June 2022 four to six weeks after emergence. Note fine root and nodulation development (courtesy, Kevin Foster, DPIRD)

reefinating[6] (where necessary, [8]), heavy applications of ground limestone to correct low pH (often 3–4 Tonne/ha, incorporated to 5 cm in autumn). In addition, tillage radish is sown to ameliorate soil compaction effects [9], improve soil structure and water infiltration, recycle nutrients [10], and provide forage. Subclover is grown to source organic N and kickstart the carbon and nitrogen (C and N) cycles for the farm's labile carbon and available nutrient pools to grow ([7]). Insecticides are not sprayed, fungicides are rarely used (and never pre-emptively), and only herbicide groups with no known long residuals are used (i.e., not group B chemicals). Low rates of synthetic fertilisers are applied (compared to district averages) in forms that do not volatilise and often are applied as foliar sprays (as are micronutrients and stimulants such as kelp) or in solution (e.g., Sulphate of Ammonia). Tolga's current main production risk is in reducing the use of synthetic N in the paddocks that are transitioning into

[6] Crushing of caprock to create topsoil.

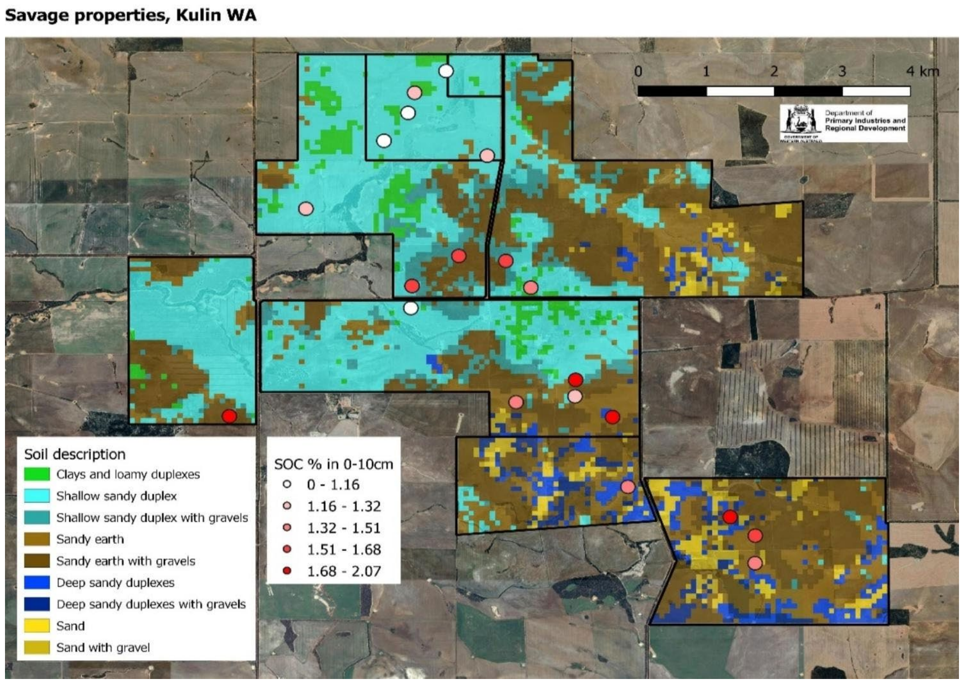


Fig. 3 November 2021 soil tests, Tolga Farm, Kulin WA, 2022 (DPIRD 2019 / Holmes et al. 2021)

its system. Organic nitrogen levels, and other nutrient cycling such as from tillage radish, in these paddocks must improve sufficiently to maintain acceptable crop yields (Brendon Savage, pers. comm. See also [7]).

Some data exists to indicate the farm's total organic carbon pool. In November 2021 the average was 1.33% to 30 cm over the sampled sites (Fig. 3[7]. see also Fig. 4 for a comparison of some of these sites to 2008 samples). This is either (a) similar to the surrounding area (Fig. 5A), or (b) as much as 40% higher than the then surrounding 100 km area (estimated 86% of land is less than 1% SOC) (Fig. 5B). Given the aim of the production system is to cycle nutrients, including carbon, the farm's potential to expand its pool of SOC – and possibly store SOC at depth out of the production zone (see [7]) - will be the focus of soil investigations by DPIRD over 2023–26.

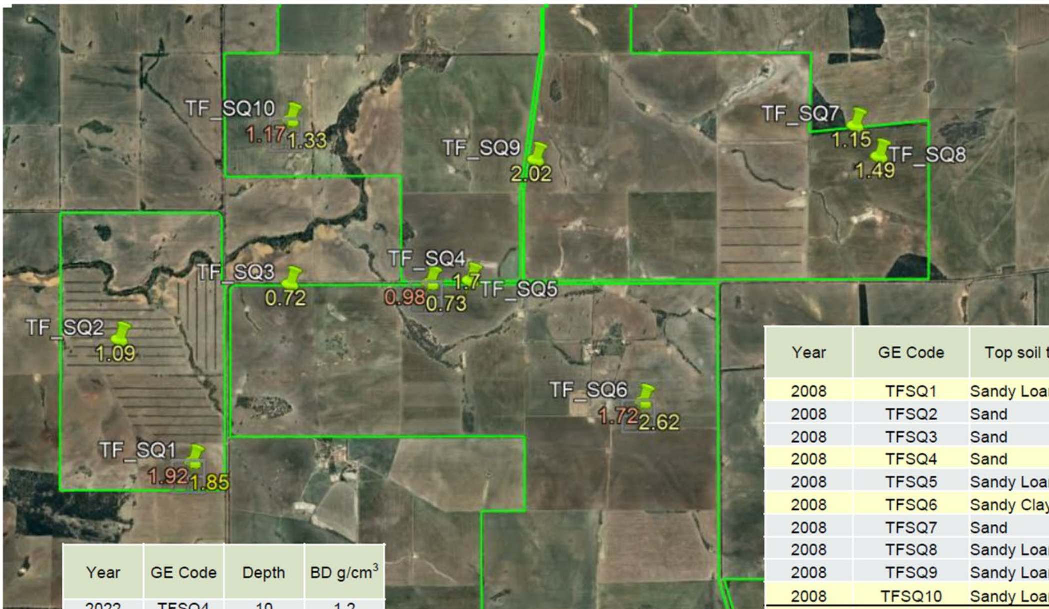
Livestock production

For 100 years Australian broad-acre rainfed farming has been underpinned by both profitable crops and livestock systems (mainly sheep and wool). However, in recent decades cropping has dominated due to comparatively low livestock income. Planfarm[8]'s average pasture area across its M4 client base, 2015-20 indicates a negative correlation between profit and livestock (Table 5). With increases in livestock and wool prices over the past decade [11], and particularly since 2017, (Figs. 6 and 7) opportunities have arisen for many farmers to achieve profitable, climate resilient, diverse, less risky farming systems [12, 13] with potentially better soil health [7, 14], than all cropping enterprises. While recent drought conditions and policy uncertainty regarding live trade shipments from WA have depressed producer prices, the OECD-FAO forecast price increases for sheep meat to 2031 as the production from world's larger exporter, New Zealand, is increasingly constrained by the rising costs of pasture due to competition from forestry, dairy and beef [15]. The re-integration of livestock and pastures back into cropping farms offer potential opportunities in terms of livestock productivity and profitability, with lower financial risk, by including biological nitrogen and synergies with cropping [16] in addition to high livestock performance (e.g., higher lambing rates, see Tables 6 and 7. For turnoff rates see Table 8 [17]). These combined factors have resulted in Tolga's steady transition to more livestock over the years.

The farm's sheep numbers, flock composition and lambing rates for 2021 are presented in Table 6. The average stocking rate over the past several seasons has been about 2.61 DSE/ha, (dry sheep equivalent) but Tolga will increase its average stocking rate over the next 2–3 years to a target of around 2.80 DSE/ha (Tables 6 and 7, note increase in breeding ewes, DSE/ha, in new system).

[7] 2 samples were tested at Apal (https://www.apal.com.au/) in Adelaide and the rest were tested at National Advantage Laboratory Services (ASPAC accredited https://www.aspac-australasia.com/certified-labs/laboratory/15) in Werribee, Victoria.

[8] PlanFarm, a major agricultural consultancy, has an extensive client base across WA and publishes annual Benchmark series outlining key production and financial performance data.



Year	GE Code	Depth	BD g/cm^3
2022	TFSQ4	10	1.2
2022	TFSQ4	20	1.6
2022	TFSQ6	10	0.9
2022	TFSQ6	20	1.3

Year	GE Code	Top soil texture	CEC	Total Org C (%)
2008	TFSQ1	Sandy Loam	4.21	1.85
2008	TFSQ2	Sand	2.33	1.09
2008	TFSQ3	Sand	1.92	0.72
2008	TFSQ4	Sand	2.4	0.73
2008	TFSQ5	Sandy Loam	3.52	1.7
2008	TFSQ6	Sandy Clay Loam	6.03	2.62
2008	TFSQ7	Sand	3.07	1.15
2008	TFSQ8	Sandy Loam	3.65	1.49
2008	TFSQ9	Sandy Loam	3.57	2.02
2008	TFSQ10	Sandy Loam	4.66	1.33
2021	TFSQ1	Sandy Loam		1.92 ↑
2021	TFSQ4	Sand		0.98 ↑
2021	TFSQ6	Sandy Loam		1.72 ↓
2021	TFSQ10	Sandy Loam		1.17 ↓

Fig. 4 2008 and 2021 Total Organic Carbon samples from 2008 Soil Quality Sites https://www.soilquality.org.au/

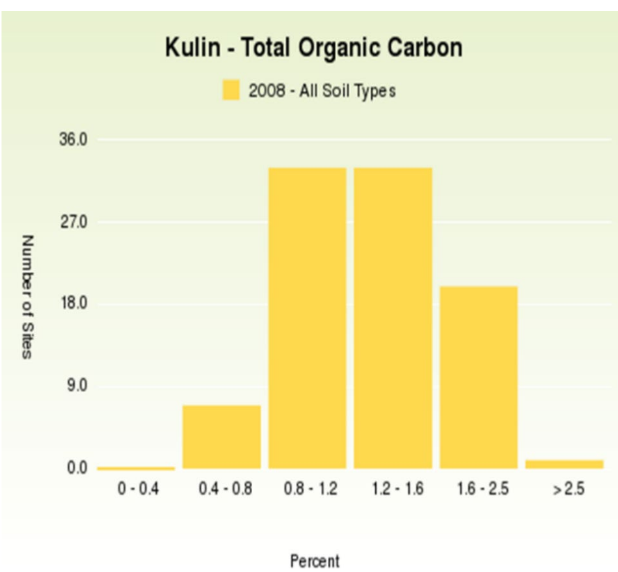


Fig. 5A 2008 Soil Quality results for Kulin Area https://www.soilquality.org.au/

The aim is to increase pasture legume content and species sown to improve climate resilience (i.e., better able to deal with false breaks, dry starts, and dry years). The key strategy applied for false starts to the season (pasture feed on offer reaches 500 kg/ha followed by 3 weeks of no growth) and dry Aprils (and drought) is confined feeding for maintenance using a blend of straw (fibre), proprietary ASP lick and spray. The proportion of the flock that is confined fed depends upon the severity of dry conditions. If weight gain is needed to finish animals at the end of the season, then cereal grain is added to this feed mixture.

The mainstay of the farm's livestock production is the turnoff of its large-framed prime multibreed lambs. The goal is to grow its prime lambs on low-cost pasture and turn them off by November each year. In addition to timely management, nutrition is the key determinant for the expression of Tolga's improved livestock genetics (high fertility, low mortality, and increased growth rates).

In 2021, with sheep at 50% on farm (50% cropping), numbers peaked at 8,600 with about 3,000 ewes (Table 6). About 4,500 ewes (Table 7) will be carried at an increased stocking rate once the target livestock model is achieved on 65% of the farm (35% cropping) by around 2024/25. The target livestock model is a ratio of about 30:40:30% respectively of high fertility composite meat sheep, self-shedders (ability to shed their own wool), and Merino / Romney crossbreds, with hybrid vigour and improved genetics.

Prime lamb analysis

Tolga's prime multibreed lambs' WAMMCO (Western Australian Meat Marketing Co-operative) slaughter statistics and lamb marking rates data, 2020–22 was analysed (Table 8). In 2022, the estimated mortality rate in multiple lamb bearing ewes was around 2%. No supplementary feeding of multibreed ewes occurred after the start of lambing in 2022. Hence the performance of ewe/lamb units was totally dependent on subclover

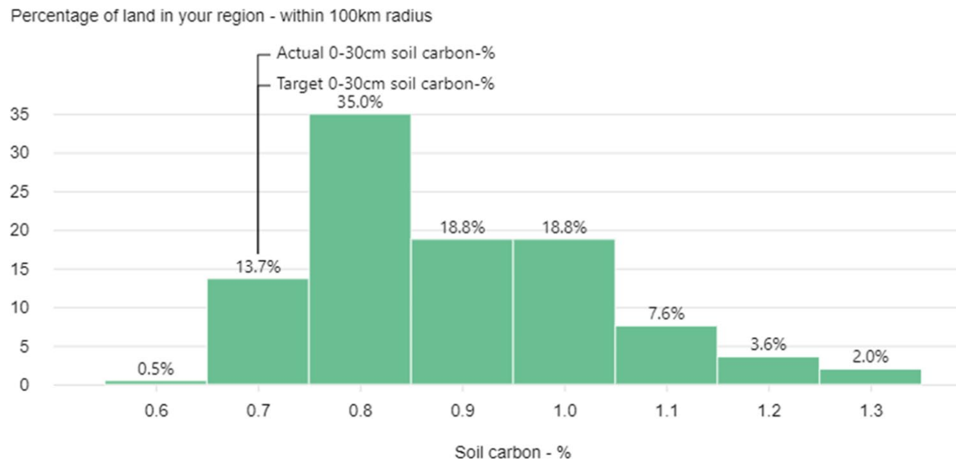


Fig. 5B LOOC-C, Landscape Options and Opportunities for Carbon Sequestration, 100 Km radius estimated SOC % https://looc-c.farm/farmDetails

Table 5 Planfarm M4 pasture area,2015-20

	Top 25% profitability	Median profitability	Bottom 25% profitability
2015	24%	31%	32%
2016	25%	29%	31%
2017	20%	31%	37%
2018	18%	33%	42%
2019	24%	32%	38%
2020	19%	29%	40%

dominated pasture grown from early May. However, this grazing system *provided sufficient energy* to ensure an average lamb marking rate[9] of 170% over the period; the grazing system also provided sufficient energy and protein to support these high growth rates. For instance, across the three years, the estimated growth rates for the 1st drafts[10] averaged 389 g/d (gm per day). Similar carcass weights for the draft of mostly twin born lambs were achieved despite different growing season rainfall over the three years (see Table 8). A 400 g/d liveweight gain is defined as fast [18]. An Australian feedlot producer survey (2020) indicated that the most frequently reported feedlot growth rate of 300–350 g/d ([19]; see also Table 6 in [20]).

The intake of green subclover by the twin born meat lambs needs to be greater than 90% of their potential from day 14 to day 123 to achieve 2022's recorded average 24.1 kg carcass weight by September 19 of that year (pers. com. D Roberts). As noted, similar results were achieved in both 2021 and 2022.

Stocking density must be maintained such that sufficient feed on offer (FOO) is available to provide both adequate animal intake and further pasture growth. Tolga's 2.61–2.80 DSE/ha stocking rate is conservative by district standards, implying stock can forage around large paddocks to find their required feed. Using Pastures from Space™, we compared the pasture growth rates of a 126 ha paddock that historically has produced well compared to the rest of the farm, with three recently renovated (recently fully incorporated into system) pasture paddocks (average 122 ha) in 2022 on the Tolga farm. The former achieved a cumulative pasture growth from May 12 to September 19, 2022, of 3.4 Tonnes of Dry Matter (TDM)/ha (130 days). The latter achieved an average cumulative pasture growth of 4.1TDM/ha. An efficient grazing system would aim to maintain FOO between 0.8-1.4TDM/ha in autumn / winter and 1.4–3TDM/ha in spring (pers. com. D Roberts). It was estimated that the lower percentiles of these targets were achieved quickly (Table 9), and that pasture growth was high, but not sufficient to explain the increased lamb growth rate needed to achieve the final average growth of 406 g/d in 2022. This suggests that the feed quality of pasture is exceptionally high; the dry matter intake of pasture increases as digestible dry matter (DMD) increases [21]. Further, Tolga's very high proportion of clover feedbase declines in quality (DMD, protein) at a slower rate than pastures with larger proportion of grasses. This suggests that Tolga's pastures could be usefully tested to establish actual energy availability for grazing sheep.

While it is difficult to provide an exact value for the metabolized energy (ME/MJ) of subclover plants growing under optimal conditions[11], South Australian data [22] indicates that, overall, subclovers have the highest DMD of up to 50 legume species tested when grown under ideal conditions (see also [21]). A summary of Vercoe's [22] data is presented in Table 10. It presents nutritional quality parameters (DMD, M/D[12], Nitrogen) across

[9] Percentage of live lambs at marking per ewes scanned.

[10] 1st batch of lambs sent to meat processor.

[11] As this can vary depending on several factors such the stage of development of the plant, and the specific growing conditions.

[12] digestible energy content at maintenance, MJ/kg.

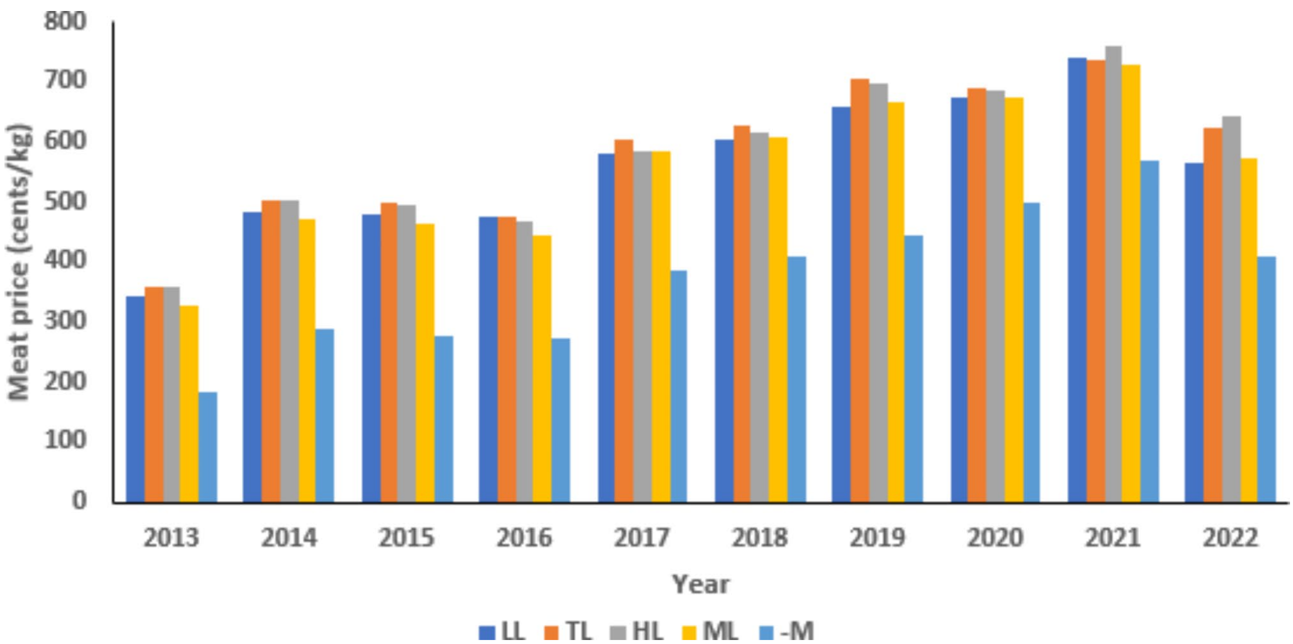


Fig. 6 WA Sheep Meat Price Indicators, 2013 ? 22, c/kg. LL: Light lamb (12-18kg), TL: Saleyard trade lamb (18-22kg), HL: Heavy lamb (22+kg) ML: Merino lamb (16-22kg), M: Mutton (18-24kg). Source: MLA

set of legumes, the average of the subset of clovers and the average of the subset of subclovers across the plants' vegetative, reproductive and senesce stages. Subterranean

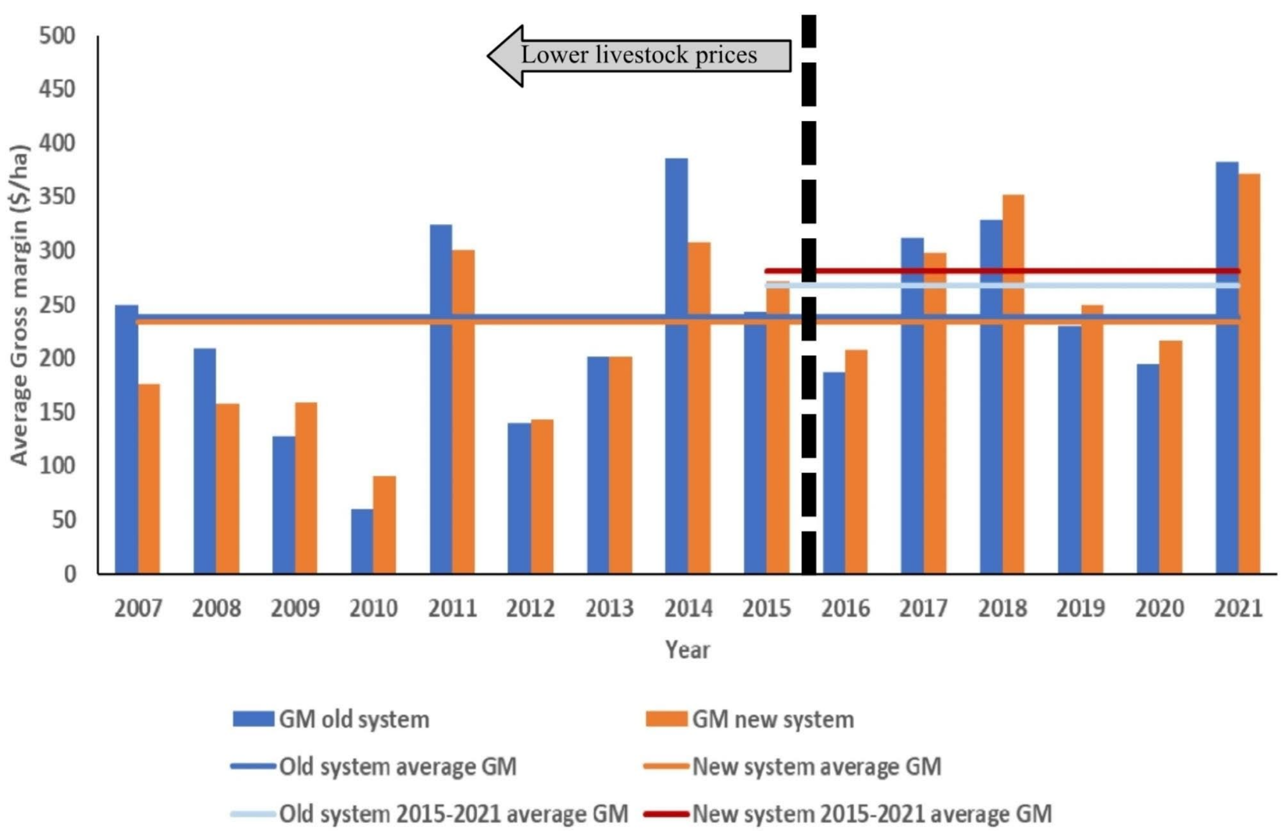


Fig. 7 Comparison of Tolga's Old (50/50 livestock/crop) and Target (65/35 livestock/crop) Production Systems over 15 years and 7 years

Table 6 Tolga livestock summary, 2021 (50% livestock, 2,600 ha, assumed morality rate of 3%)

	Rams	Ewes	Wethers	Hoggets	Ram lambs	Ewe lambs	Lambing rate	Total
Merino	32	2405	0	594	660	660	120%	
Terminal*	37	0	0	0	1109	1109	170%	
Dohne	6	188	0	169	169	169	180%	
Shedders	7	220	0	165	165	165	180%	
Dry ewes		247	0	0	148	148	120%	
Total hd	82	3060	0	928	2252	2252		8574
DSE**	164	5508	0	1114	0	0		6786
DSE/winter grazed ha	0.06	2.12	0.00	0.43	0.00	0.00		2.61

*Sire used for breeding meat lambs https://kippax-farms.co.uk/terminology/what-is-a-terminal-sire

**Dry sheep equivalent https://www.mla.com.au/extension-training-and-tools/feedbase-hub/persistent-pastures/grazing-management/stocking-rate

Table 7 Tolga livestock summary, target (65% livestock, 3,380 ha, assumed mortality rate of 3%)

	Rams	Ewes	Wethers	Hoggets	Ram lambs	Ewe lambs	Lambing rate	Total
Merino	40	1419	0	350	993	993	140%	
Terminal	40	1419	0	350	1206	1206	170%	
Shedders	40	1703	0	420	1277	1277	150%	
Total hd	120	4541	0	1120	3476	3476		12,733
dse	240	8174	0	1344	0	0		9758
DSE/winter grazed ha	0.0	2.35	0.00	0.39	0.00	0.00		2.80

Table 8 Key production statistics derived from analysis of WAMMCO slaughter sheets and farm mating, and lamb drop data for multibreed prime lambs (curtesy of Tolga, analysis by Danny Roberts, Senior Veterinarian, DPIRD)

	2020	2021	2022
Mating	Mid December, 35 days		
~ Lamb birth	Late May		
Decile	2	9	5 (?)
Estimate marking percentage	160	170	180
Multibreed ewe x White Suffolk ram, ~ number of lambs	~ 1810, three-year average		
~ Period	19 Sept – 16 Nov		
Estimated average lwt/head, kg	53	53	60
Average cwt/head, kg	23	23	26
GSR, mm	168	359	244
Total cwt, kg/mm GSR	213	125	146
Average days to turnoff	149	151	156
Estimated days from lamb drop to 1st draft	128	122	123
Estimate growth rate from drop until 1st draft (g/h/d)	375	388	406

clover's mean energy (its quality) appears to have had the slowest deterioration.

Pasture production: removing constraints: acidity, pesticides, fungicides, herbicides, and large N applications

Chen et al. [23] found the impact of liming to reduce acidity on prime lamb production on acid soils (pH 4.5) in NSW significantly improved the yield of *high-quality* feed (at vegetative and mature stages) but reported no significant impact on total DM (unlike the comparison

Table 9 Feed On Offer Calculations (FOO), Tolga selected paddocks, 30 June – 20 September, 2022

	Historical well producing paddock, Tolga Farm	Recently fully renovated (limed etc, see text) paddocks, Tolga Farm
Target FOO of 0.75TDM/ha	Week of 30 June to 06 July	Week of 01 to 07 June
Target FOO of 1TDM/ha	Week of 21 to 27 July	Week of 16 to 22 June
Week of 14–20 September	Estimated FOO of 1.7TDM/ha	Estimated FOO of 2.46TDM/ha

DPIRD, Pastures from Space™

Table 10 Selected Summary Data: Mean nutritional traits of annual legumes in South Australia at vegetative, reproductive, and senesced stages of development

Stage of plant development	Nutritional Trait	Legumes	Clovers	Sub Clovers
Vegetative	DMD%	73.7	74.2	73
	M/D* (MJ/kg)	11	11	10.8
	N%	3.8	3.9	4.2
Reproductive	DMD%	66.7	66.9	71.9
	M/D (MJ/kg)	9.8	9.8	10.7
	N%	2.7	2.5	2.8
Senesced	DMD%	55.7	54.8	57.4
	M/D (MJ/kg)	7.8	8.1	8.2
	N%	2	2	1.9

* digestible energy content at maintenance

Vercoe 2017

made above). That is, liming increased and extended FOO by increasing the proportion of clover in the sward and consequently substantially increased lamb weights. The difference in weights was attributed to the difference in forage quality.

Pesticide applications can also impact on pasture quality. The direct adverse use of pesticides application on rhizobia has also been noted for several decades and indirect pesticide residues may also stunt fine root development and interfere with the bacterial infection process [24].

Pesticide use on Tolga is limited to Imidacloprid [25] which is used as a dressing on barley seed at planting as it is susceptible to cut worm (*Agrotis spp*) [26] and web worm [26] when sown on former pastures. Evidence exists that fungicides (used sparingly on Tolga) and herbicides such as MCPA and 2,4-D can also kill rhizobia with similar impacts to pesticides [27, 28]. Table 4 indicates that MCPA is used on Tolga; note as the farm's Certified Sustainable [29] process tests for residue at levels more stringent than organic certification it may be inferred that the residual effect on pasture from this chemical is likely to be low[13]. Nonetheless, any chemical use may prune legume roots, so potentially increase susceptibility to disease, moisture stress and micronutrient deficiencies [30]. Dry conditions may retard microbial breakdown of chemical residues (especially in alkaline soils) before legumes germinate and affect rhizobial survival and symbiosis [31]; further glyphosate applications before sowing may translocate into the soil and harm seedlings and symbiotic mycorrhizal fungi [32]. This underlines Tolga's practice to use foliar application of micronutrients to pastures, particularly after grazing (B. Savage pers. comm.). Nutrition in solution, where possible, is also applied to weeds in preference to chemical use, as it improves the palatability and digestibly of weeds, particularly capeweed (*Arctotheca calendula*), which enhances their control as well as providing valuable nutrition to livestock (B. Savage, pers comm).

The effects of soil compaction from machinery and sheep movement are increasingly addressed using deep and wide rooted tillage radish (*Raphanus sativus*) [9]. The Savages observe that subclover appears to respond exceptionally well when grown with tillage radish.

Crop production

Several key synergies exist between the pasture and crop phases. Synthetic N application is 8 kg/ha in paddocks fully transitioned to the ASP system (Table 3). There is evidence from studies in the United States that application of synthetic N at levels more than that needed to replace grain removal, has resulted in net losses in soil C [33] and the researchers stated that excess N promotes the decomposition of residues and SOM (soil organic matter). SOM consists of around 58% SOC [34]. Maintaining a large cycling pool of SOC / SOM is key to maintaining biological activity as well as water holding capacity and cation exchange capacity (CEC), particularly in WA's highly weathered soils [14]. Tolga's recent ongoing transition to double pasture / single crop phases (65% pasture / 35% cropping) implies increased availability of SOM over seasons [35], and organic N for crops [30], [16]). The most recent winter sown cereal harvest (2022) provides evidence of substantial lifts in grain yields (up to 4.2T/ha) in fully transitioned paddocks following two pastures (B. Savage, pers. comm.) compared to previous yields which were around industry averages (Table 11). Research evidence on the impact of legume phases on subsequent crop yields by by Loi et al. supports the observations made by Tolga [16].

Early crop grazing is an effective frost mitigation strategy as well as providing additional fodder to livestock [36]. Crops to be grazed have the same liquid nutrition applied to them as weeds to enhance their palatability and digestibility (B. Savage, pers. comm.). A legume pasture phase can reduce persistent weed burdens (particularly herbicide resistant ryegrass) in the subsequent crop phase [37]. In addition, rotating between crops and

Table 11 Estimated crop yields

	Yields: T/ha					
	Decile 3		Decile 5		Decile 8	
	Sandy	Clay	Sandy	Clay	Sandy	Clay
Tolga barley (1,500 ha) Old system	1.4	1.3	2.3	2.5	3.3	3.5
Tolga barley (810 ha) Target system	As above + 0.5					
Planfarm barley, M4 (top 25%)	2.07 (2009)		3.01 (2007)		3.12 (2014)	
Planfarm barley, M4 (median)	1.84 (2009)		2.46 (2007)		2.78 (2014)	
Tolga oats (1,000 ha), Old system	1.3	1.2	2.2	2.4	3.2	3.4
Tolga oats (1,010 ha), New system	As above + 0.5					
DPIRD Seasonal Updates (2009, 2007)	1.80 (2009)		1.90 (2007)			

[13] Other chemicals contenders for residual carryover such as triazines (simazine & atrazine), sulfonyl urea ((SU) Ally™, Logran™ and Glean™), imidazolinones (Spinnaker™, Onduty™ & Raptor™) are not used. SU residues can persist for several years.

Table 12 Tolga Old (50/50 livestock/crop) and (65/35 livestock/crop) Target Systems, Planfarm Benchmark (median) and Planfarm Top 25%, 2007–21 (15 years)

	Old system	Target system	PlanFarm Median	Plan-Farm Top 25%
Income ($/ha)	392	373	562	734
Cost ($/ha)	154	140	314	353
GM ($/ha)	239	234	248	382
CV in GM %	39%	35%	50%	39%
EBITDA ($/ha)	194	189	203	334
CV in EBITDA (%)	48%	42%	60%	44%
Emissions (kg/ha, CO_2e)	511	578		

Table 13 Tolga Old and Target Systems, Planfarm Benchmark (median) and Planfarm Top 25%, 2015–21 (7 years)

	Old system	Target system	PlanFarm Median	Plan-Farm Top 25%
Income ($/ha)	413	414	621	812
Cost ($/ha)	144	133	346	400
GM ($/ha)	268	281	274	412
CV in GM %	27%	23%	41%	38%
EBITDA ($/ha)	219	232	225	359
CV in EBITDA (%)	34%	27%	50%	39%
Emissions (kg/ha, Co2e)	516	558		

broadleaf pastures combined with judicious timing of chemical application can reduce the incidence of diseases [37] and reduce the likelihood of chemical resistance. The owners estimate that the farm uses as much as 40% less (by volume) of chemicals compared to producers within the district (see Table 3). Barley and oats are not only relatively more frost tolerant [38] but, compared to wheat, also provide improved summer grazing stubble and better-quality straw for confined feeding rations [39]. Stubble palatability and digestibility is enhanced by supplementary nutritional (high protein) licks; straw palatability and digestibility is further enhanced by spraying nutritional supplements during windrow (Brendon Savage, pers.com; see also [40–43].

Economics

The farming system economics modelling team at DPIRD conducted a model simulation of Tolga's 50/50 livestock / cropping system (current until 2021) and its target 65/35 livestock / cropping system as steady state models to remove inter season variability and off farm financial revenue. The models use historical prices and seasons to analyse economic performance over the past 15 and 7 years. Tables 12 and 13 also compare these results with the M4 PlanFarm Benchmark data for these periods [44]. Tolga's profitability has improved relative to the PlanFarm median – it is slightly above it – but its already low variance in profit has further declined. That is, while it generates roughly the same Gross Margin and EBITDA[14] as the PlanFarm Benchmark (median), it has nearly half the variance in its profit flow (Tables 10 and 11). Low variability in their profit flow has been central to financing the farm's steady expansion. Research has indicated that most farm managers are moderately risk adverse [45, 46].

On average 30–40% of variable cost is spent on fertilisers and 20–30% on weed and disease control. The synergies between its crop and livestock phases ensures that the cost of nitrogen-based fertilisers and pest management is significantly lower than the average farmer. Very low inputs ensures that costs do not become unmanageable when input prices escalate. This ensures the farm either makes a profit or does not suffer heavy losses in poor seasons. The owners are happy to forgo some profit to ensure a low-risk business. Low variability in their profit flow has been central to financing the farm's steady expansion. Tolga is 57% larger than the PlanFarm M4 average farm of 3,300 ha in 2021.

Also note the farm's comparatively low emissions, which are a function of its low stocking rate and its low inputs. Emissions (T/CO_2e) are estimated to be a third to a half of the industry average for mixed farms. Kharel et al. [3] used bioeconomic modelling to inform the profitability and emissions profiles of land use sequences across south-western Australia. Crop dominated systems to the north and east had lower emissions than pasture dominated systems in the south because of the higher levels of enteric methane emissions. Kharel et al. [3] estimated the Co2e/ha emissions of Corrigin (M4) farm with 50/50 livestock and crop to be around 850–900 kg CO2e/ha compared to Tolga farm's 50/50 livestock/crop system of around 540 kg CO2e/ha. Tolga's crop emissions are estimated to be below the estimate industry range (oats, 333 vs. 486–1100) or at toward the bottom of industry range (barley 331 vs. 269–1147) and considerably below the estimated industry average; these figures are presented in Table 14. Table 14 also indicates that Tolga's sheep enteric methane emissions are around 70% of the range of enteric emissions of the M4 region [47].

Future research

To enhance the understanding of livestock performance on Western Australian farms, it is recommended that further research be conducted at Tolga farm (Kulin) to establish the link between pasture plant chemistry (such as metabolizable energy, crude protein, phosphorus, potassium, sulfur, etc.) and sheep physiology and growth rates. Additionally, exploring the relationship between plant chemistry and soil biology, soil chemistry, and soil

[14] Earnings before interest, tax, depreciation, and amortization (cash profit).

Table 14 Tolga Emissions: Old (50/50 livestock/crop) and (65/35 livestock/crop) Target Systems vs. WA Benchmarks

GHG emissions (kg CO2e/ha)	Tolga: 50/50 livestock/pasture	Tolga: 65/35 livestock/pasture	Industry	Source
Barley	382	331	269–1147 (All)	CBH/WOA/DPIRD [47]
Oats	384	333	486–1100 (All)	CBH/WOA/DPIRD [47]
Sheep	696	738	1000–1100 (M4)	Kharel et al. 2022

physics would provide additional valuable insights. This research should be conducted within the broader context of the entire farming system, considering its management practices, and further within the ASP consulting and peer-to-peer system. We also propose that research be undertaken to investigate around the high levels of sheep and pasture performance and on reduced enteric methane emissions.

Implications for policy and industry development

This case study highlights the importance of promoting lower input mixed farming systems in WA's public policy. These innovative systems have the potential to be both profitable and environmentally friendly by reducing greenhouse gas (GHG) emissions and emissions intensity and building soil carbon. By measuring carbon cycling and establishing farm net carbon levels, farmers can gain access to new markets that increasingly prioritise sustainability. For instance, recently Tolga partnered with WA's fourth largest brewer (Rocky Ridge) and the globe's largest maltster (Bortmalt) to create single origin source of a low emission, Certified Sustainable barley supply chain [48, 49]. The price premium paid for Tolga's barley will assist in promoting industry adoption of low net carbon technologies.

Western Australian public policy also aims to promote new farming systems that mitigate climate risks, as an alternative to continuous cropping systems. The case study provides evidence of the synergies between livestock and cropping, particularly in terms of weed management, soil health and biological nitrogen supply from legumes to subsequent cereal crops. It also demonstrates that a sustained focus on soil health, with reduced chemical and synthetic fertilizer inputs (reduced GHG), can enhance both crop and pasture productivity. The long-term economic analysis conducted over 7 and 15 years in this case study is valuable as it showcases the system's sustainability while highlighting its sensitivity to relative prices. The use of a combination of case study that generates detailed specific farm data from manager's records, simulation modelling and industry benchmarks can serve as a powerful tool for producers seeking low-cost, low-risk means to explore alternative scenarios for their farm systems.

While the conventional elements of Tolga's system can be transferred to other contexts, the full business value of the system lies in the integration of all its components (a whole of system approach), including its membership in the ASP group. This membership underscores the importance of localised decision-making within a supportive network of like-minded peers when adopting and implementing change. Within this high-trust support network, research and development are fostered, championed, and refined. This aligns strongly with WA's public policy to promote farmer peer-to-peer learning groups.

The attention given by Tolga farm to management details, particularly animal husbandry skills, reducing business risks, and long-term goals, highlights the significance of continued investment in farm business and risk management training. While Tolga's production system may be unusual, the challenge for DPIRD is to understand and extend the key principles of this profitable system to the rest of the livestock and cropping industries. Sharing the outcomes and success of this business can support other producers in adopting critical practices for their own production systems. This, in turn, can create alternative pathways or approaches that maintain sustainable profitability and resource management in the face of increasingly extreme climatic events [50].

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