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An investigation of pathways for rebuilding Australia's sheep flock

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ABSTRACT

Context. A significant opportunity remains to further increase the supply of premium sheepmeat products to Australia's customers, which requires a more rapid rebuilding of the national sheep flock. To help meet this challenge, developing relevant information for sheep producers to assist them to achieve a profitable flock-rebuilding outcome is viewed as highly desirable. **Aims.** (1) Develop flock-rebuild scenarios that track inventory, cashflow, profit and loss, and the overall balance sheet over a 5-year projection. (2) Model the impact on flock-rebuilding pathways of exposure to variation in supplementary-feed costs, purchase of stock and price received for sale animals and flock structure. (3) Model variation in benefits and costs for a range of production zones, enterprise types and flock-age profiles. **Methods.** Fourteen flock-rebuilding pathways were assessed for up to nine flock types, using a spreadsheet model that tracked inventory, cashflow, profit and loss, and the overall balance sheet over 5 years. **Key results.** The top four pathways for profitability and capacity to rapidly rebuild flock numbers include retention of more older ewes, purchasing young ewes, purchasing older ewes (mostly 5–6-year olds) in Merino and Merino-cross flock types only and joining ewe lambs in Maternal and Cleanskin flock types only. These pathways were not sensitive to variation in the cost of supplementary feed, stock prices or flock structure, although joining Merino ewe lambs became one of the top four pathways when feed costs were lower. **Conclusions and implications.** The well established practices of retaining ewes for longer and purchasing ewes, especially young ewes, have the most potential to both rapidly and profitably rebuild flock numbers. However, joining ewe lambs, particularly in Maternal and Cleanskin flocks, can also profitably contribute to rapid flock rebuilding. While reducing reproductive wastage or increasing reproductive potential were mostly profitable, they could not rapidly rebuild flock numbers. In contrast, accelerated lambing systems can rapidly rebuild flock numbers, but are only marginally profitable.

Keywords: drought, joining, modelling, profitability, rebuilding, reproduction, restocking, sheep.

Introduction

The outlook for the future of Australia's sheepmeat industry appears very positive, with forecast export demand for lamb and mutton in particular increasing in the foreseeable future (MLA 2021), likely beyond the ability of the industry to fully supply it. The Australian sheep flock, following a long period of decline from a peak of 173.1 million head in 1990 (ABS 1991), reached a historic low of 63.5 million in 2020 (ABS 2021*a*; MLA 2021), due to a combination of low wool prices, drought, competition from other enterprises, welfare concerns and producer lifestyle choices (Brien *et al.* 2011). During that period, there has been a large increase in the proportion of ewes in the national flock, from 44% of total sheep numbers in 1990 to 63% in 2021, and increases in the proportions of Merino ewes bred to non-Merino rams and Merino cross and non-Merino ewes mated for speciality lamb production (ABS 1991; MLA 2021). Meanwhile, the total of number of lambs slaughtered annually in Australia has gradually risen from a low point of 15 million in 1995, to between 20 to 23 million over the past decade (ABS 1996, 2021*b*). Much of these trends in the national flock have been in response to the higher relative prices of sheep meat compared with wool, especially since the turn of the millennium in 2000 (Swan *et al.* 2007).

Although flock rebuilding has commenced (sheep numbers in 2023 are forecast to rise to 75.4 million (MLA 2021), there remains a significant opportunity at both an enterprise and industry level to further increase the supply of premium sheepmeat products to Australia's customers, benefiting the whole supply chain. To fully capture this opportunity, a more rapid rebuilding of the national sheep flock is required than is currently the case. A key element to this will be equipping sheep producers with the necessary skills, confidence and ability to profitably rebuild their flocks.

This paper reports the findings of a study that examines alternative pathways to rebuild flock size following periods of destocking, most often as a consequence of drought. In particular, the objectives of the study were to

a. Develop flock rebuild alternatives that track inventory, cashflow, profit and loss and the overall balance sheet over a 5-year projection.
b. Model the impact on these rebuild strategies of exposure to variation in supplementary-feed costs, purchase prices of stock and prices received for sale animals and flock structure.
c. Model variation in benefit and costs for a range of production zones (pastoral, mixed farming, high rainfall), enterprise types and flock age profiles.
d. Identify and report intangible barriers to flock rebuilding.

Materials and methods

Flock rebuilding pathways

Flock rebuilding pathways generally fall into the following broad categories: (i) retaining breeding ewes for longer than normal, culling less or purchasing more ewes from outside the flock; (ii) reducing reproductive wastage by improving fertility and lamb survival; (iii) boosting reproductive potential via increases in ovulation rate, and (iv) joining at a younger age and joining more than once a year. The full range of pathways assessed for economic merit and their ability to contribute to flock rebuilding over a 5-year period are listed in Table 1.

(i) *Retaining more ewes for breeding by selling at an older age than normal* is one of the traditional methods that sheep producers have employed to rebuild flock numbers. Purchasing ewes from outside the flock, generally either as ewe lambs or hoggets, or as cast-for-age breeding ewes of 5–6 years of age is also a traditional method of flock rebuilding available to sheep producers.

(ii) *Reducing reproductive wastage by improving fertility and lamb survival*. Improving fertility in the narrow sense of increasing the proportion of ewes that lamb (predicted from pregnancy-scanning results) is a possible flock-rebuilding pathway. However, as average fertility in mainly Merino flocks in Australia has been reported to be in the range of 86–90% (Kleemann and Walker 2005; Fowler 2007; Allworth *et al.* 2017), the opportunity to improve fertility in most Merino flocks is likely to be limited. Notwithstanding, re-joining ewes scanned as once-dry, rather than twice-dry as a flock rebuilding pathway has been included in this study. The available evidence suggests that the subsequent reproductive performance of once-dry ewes is only 10% below that of their flock contemporaries (F. Brien, unpubl. data; K. Atkins, unpubl. data), in contrast to twice-dry ewes that have a much lower performance and should be culled (Lee and Atkins 1996; Hatcher *et al.* 2018).

Twin-lamb survival commonly does not exceed 70% in Australia (Hinch and Brien 2014). Therefore, there is considerable scope to reduce this form of reproductive wastage.

(iii) *Boosting reproductive potential via increases in ovulation rate*. This category encapsulates a range of approaches, including improving ewe nutrition pre-joining and into the joining period, changing the joining period from spring/summer into late summer/autumn, to align with the peak of the breeding season to maximise ovulation rate and pharmacological approaches such as vaccination against androstenedione (Ovastim).

Providing improved nutrition pre-joining and into the joining period, either as additional high-quality green pasture allowance or via supplementary feeding is often referred to as 'flushing' (Heape 1899). Due to the timing of joining on most Australian farms falling between November and April, provision of additional green pasture at that time is not considered practical or needs to be provided via special-purpose pastures, such as lucerne or via irrigation. A more feasible scenario for the majority of sheep producers is supplementary feeding of cereal grains and legumes, with considerable amount of Australian research having been conducted on feeding lupin grain. Most early trials fed lupins from 14 days before joining until Day 17 of joining, a total of 31 days (Knight *et al.* 1975; Brien *et al.* 1977; Croker *et al.* 1985). However, later research suggested that ewe flocks need only 14 days of lupin supplement, if mated within their normal breeding season when not in anoestrus (Gaunt *et al.* 2017) or, if mated earlier, were also synchronised using the 'ram effect' (Nottle *et al.* 1997). In the present study, it was assumed that only 14 days of lupin feeding was required to obtain an average increase of 10 lambs born per 100 ewe mated.

The pharmacological agent Ovastim has increased ewe reproductive rates in Australian studies. Across a number of sheep breeds, Geldard *et al.* (1984) reported an average response of 23 extra lambs born per 100 ewes treated with Fecundin (now marketed as Ovastim). The present study assumed that an increase of 20 extra lambs born per 100 ewes could be obtained from treatment of ewes with Ovastim.

(iv) *Joining at a younger age and joining more than once a year*. The adoption of ewe lamb joinings has increased dramatically in recent years, particularly among maternal

Table 1. Flock-rebuilding pathways examined in the study.

Flock-rebuilding pathway category and description
(i) Retain ewes for longer than normal, cull fewer or purchase more
Retain and join 5½-year-old ewes for 1 year longer; retain 200 in Year 1, retain 150 in Year 2 and retain 100 in Year 3
Retain more young ewes; reduce culling of ewe lambs by 5%. Undertake in Years 1–3
Buy 200 ewe hoggets in Year 1 only
Buy and join 200 5½-year-old ewes in Year 1 only
(ii) Reduce wastage by improving fertility and lamb survival
Re-join once-dry ewes (identified at scanning). Undertake for 5 years
Increase twin lamb survival; supplement twin-bearing ewes in late pregnancy to gain 0.5 of a condition score by lambing. Undertake for 5 years
(iii) Boost reproductive potential via increases in ovulation rate
Supplement ewes pre-joining. Undertake for 5 years
Flushing with lupins 1 week prior and 1 week into the joining period. Undertake for 5 years
Inject Ovastim pre-joining. Undertake for 5 years
(iv) Joining at a younger age and joining more than once a year
Join ewe lambs. Undertake for 5 years
Accelerated lambing – Type 1. Join ewe flock every 8 months, i.e. three times in 2 years. Undertake for 5 years
Accelerated lambing – Type 2. Split ewe-flock system. Dry ewes are removed to a second flock and a mating opportunity is provided every 4 months. Undertake for 5 years
(v) Other
Increase Merino by Merino matings by 200 ewes in Year 1 and 2
Use sexed semen that is sorted to produce only female progeny. The flock must be mated by artificial insemination

ewe breeds (Thompson *et al.* 2021) and Merino crosses used for prime lamb production. It is therefore logical to study the potential of joining ewe lambs as a flock-rebuilding pathway.

Two types of accelerated lambing systems are considered. First, a single flock is mated at 8-monthly intervals. Second, a joining opportunity is provided every 4 months by splitting the flock into two, with those scanned as dry being moved to a second flock in a modified STAR system described by Lewis *et al.* (1996) and run at Turretfield Research Centre in South Australia from 2008 to 2011, using Merino ewes (Smith *et al.* 2012). When results were calculated on an annualised basis, the system was able to produce 58% more lambs born (on the basis of scanned fetuses) at 1.83 fetuses per ewe mated, than the annual rate of 1.15 fetuses scanned, as established in extensive surveys of Merino flocks in South Australia in the 1990s (Kleemann and Walker 2005).

(v) *Other*. Increasing Merino × Merino matings was examined in the study as sheep producers with dual-purpose Merino flocks (where some ewes are mated to terminal sires and others to Merinos) may consider it as a flock-rebuilding opportunity. At an industry level, there is also concern about maintaining a sufficient number of pure Merino ewes to produce enough apparel wool in Australia to meet demand. Finally, the novelty of using sexed semen that favours production of female progeny was the main reason for including this technique in the study as a potential flock-rebuilding pathway.

Flock types examined

Nine flock types were examined in the study, to represent the majority of sheep types and sheep-producing regions in Australia. These were

- Self-replacing Merino ewe flocks: dual-purpose, wool-focussed and Merinos in the rangeland zone
- Merino-cross ewe flocks: Merino ewe × Terminal sire, Merino ewe × Border Leicester sire, Border Leicester × Merino ewe crossed with a terminal sire
- Self-replacing Maternal ewe flock
- Self-replacing Cleanskin ewe flocks, in the agricultural and rangeland zones.

Modelling

An Excel model was constructed to track stock inventory, cashflow, profit and loss and an overall balance sheet projected forward for 5 years for each flock-rebuild scenario. The analysis process used was a partial discounted cash-flow budget (Malcolm *et al.* 2005). As a starting point, it was assumed that each property was 20% below its optimum stocking rate, with a breeding ewe flock of 1000 ewes and a target of 1250 ewes to reach. This was to simulate a situation that, for one or more reasons (drought, reduction in stock numbers to make way in the past for increased cropping activity or other enterprises, etc.), each property has become understocked and the owner/manager has chosen to rebuild sheep numbers.

Standard purchase prices were assumed to be A$300 a head for 1.5-year-old ewes (except for Merino × Border Leicester ewes, which were A$325 a head) and A$200 a head for 5.5-year-old ewes. Standard sale prices were assumed to be A$150 a head for wether lambs and A$250 for ewe lambs, A$250 a head for 1.5-year-old cull ewes and A$175 a head for 5.5-year-old, culled-for-age ewes. Standard supplementary-feed costs were A$260/t. These assumed standard purchase and sale prices and supplementary-feed costs were held constant during the 5 years of the projected stock inventory, cashflow, profit and loss and an overall balance sheet. More detailed assumptions on production levels, the costs and the selling prices for sheep, lambs and wool are provided in Supplementary material. These values were initially obtained from averages of Pinion Advisory client records and then validated with a project reference group, with members from each of the pastoral/rangeland, agricultural (mixed farming) and high-rainfall zones. Given the often-diverse nature of these geographical regions, it is unrealistic to expect that results based on the assumptions in this study can accurately reflect the range of individual property circumstances, other than provide general guidance.

A number of parameters were calculated to summarise and compare the impacts of flock-rebuilding pathways, including net present value (NPV, in A$), NPV/dry sheep equivalent (DSE; in A$), internal rate of return (%) and benefit–cost ratio (BCR), calculated over a period of 5 years. A discount rate of 3.5% per annum was applied to the calculation of cash flows (and thus NPV, BCR and internal rate of return). Some of the measures are unable to be calculated in all situations. For example, for flock types that are not self-replacing, economic assessments were mainly limited to category (i) flock-rebuilding pathways, in which ewes were either retained in the flock longer than normal, fewer ewes were culled at earlier ages or additional ewes were purchased from outside the flock. None of the parameters used, on their own, are sufficient to fully describe the relative profitability and utility of the various flock-rebuilding pathways. A summary of the strengths and weaknesses of each economic measure is given in Table 2. NPV/DSE values are the primary results provided and discussed in this study and, where these are unable to be calculated, BCRs are provided. Where appropriate, NPVs are also discussed.

In addition to economic parameters, the effect of flock-rebuilding pathways on DSE has been calculated and compared with the required increase of 669 DSE to fully restock the modelled property.

Sensitivity analyses

Sensitivity analyses were undertaken to account for variation in supplementary-feed costs, purchase of stock and price received for sale animals, variation in flock age profile and discount rate. Two of the nine flock types, the self-replacing dual-purpose Merino and self-replacing Maternal ewe flock types, were subjected to sensitivity analyses of variation in supplementary-feed costs, purchase, sale prices of stock and discount rate. The effect of variation in flock age profile was examined only in one flock type, namely the self-replacing dual-purpose Merino.

Table 2. The strengths and weaknesses of the economic measures of flock-rebuilding pathways studied.

Economic measure	Strengths	Weaknesses
Net present value (NPV) or NPV/ha	Indicates total profit and scale of the flock rebuild. Higher profit is often associated with more stock numbers	Does not provide the investment efficiency (profitability) aspect to the pathway
NPV/dry sheep equivalent (DSE)	Captures the profitability of the pathway	Does not provide the relative impact of the pathway on the flock rebuild and cannot be calculated in flocks that are not self-replacing
Internal rate of return (IRR)	Good indication of profitability of each rebuild option	Cannot be calculated for pathways that do not have an initial capital outlay
Benefit–cost ratio (BCR)	Another metric for the profitability of different pathways	Can show quite different results depending on cost structure

Supplementary-feed costs

The effect of 23% lower (A$200/t) and 23% higher (A$320/t) costs of supplementary feed were examined, in addition to the standard supplementary-feed cost assumed to be A$260/t.

Purchase and sale prices

The effect of 20% lower and 20% higher purchase and sale prices were examined, in addition to the standard purchase and sale prices of sheep.

Flock age profile

The effect of running six ewe-age groups rather than the standard assumption of four age groups was examined. Note that a lower scanning percentage (112% in mature ewes and 103% in maiden ewes) was assumed than the standard values of 145% and 120% respectively, for a self-replacing dual-purpose Merino flock type.

Discount rate

The effect of a discount rate of 7% per annum was examined, in addition to the standard discount rate of 3.5% per annum.

More details on input assumptions, inventory, cash flow and profit and loss are given in the Supplementary material.

Results

The economic merit of the alternative flock-rebuilding pathways for each of the nine flock types examined in the study are presented in Table 3 and are primarily based on NPV/DSE (A$), except for the Merino-cross flock types, which are assessed by benefit–cost ratios.

Re-joining of ewes scanned dry (scanned after first mating opportunity; Pathway 5) ranked first for all flock types except a wool-focussed Merino flock. Retaining older ewes (Pathway 1) also ranked highly across all flock types, as did increasing twin-lamb survival (Pathway 6) and buying ewe hoggets (Pathway 3). Ovastim injection (Pathway 9) ranked within the top three pathways for self-replacing Maternal and Cleanskin flock types and within the top six pathways for self-replacing Merino flock types. Buying aged ewes (Pathway 4) also ranked within the top six pathways for self-replacing Merino and Merino-cross flock types. Finally, joining ewe lambs (Pathway 10) ranked within the top six for self-replacing Maternal and Cleanskin flock types.

For all scenarios considered, the top six flock-rebuilding pathways had a higher NPV/DSE value for utilising the additional feed on the understocked properties, than did returns from running agisted stock or from making hay and selling it (results not shown).

Of the remaining flock-rebuilding pathways, retaining more young ewes (Pathway 2), joining ewe lambs (Pathway 10) and increasing pure Merino matings (Pathway 13) for self-replacing Merino flock types were profitable, but returned less than did the top six strategies. Supplementing ewes pre-joining with cereal grains (Pathway 7) was only marginally profitable for self-replacing Maternal and Cleanskin flock types, but below break-even for self-replacing Merino flocks. Accelerated lambing systems (Pathways 11 and 12) were barely break-even for self-replacing Merino flock types and were slightly unprofitable for self-replacing Maternal and Cleanskin flock types. Flushing with lupins (Pathway 8) was one of the top six flock-rebuilding pathways for Maternal and Cleanskin flock types, except for the rangeland zone, but was lowly profitable in self-replacing Merinos except in the rangeland zone, similar to the Cleanskin type. Finally, use of sexed semen was highly unprofitable (Pathway 14) in all situations where artificial insemination is not the normal practice.

Contribution to flock rebuilding

The number of additional DSE generated over 5 years from the use of the top six flock-rebuilding pathways are illustrated below for a self-replacing dual-purpose Merino flock (Fig. 1) and a self-replacing Maternal flock (Fig. 2).

The target DSE of 669 (equivalent to an extra 250 ewes) is the number required to completely restock the property,

Table 3. Net present value/dry sheep equivalents (A$) of flock rebuild pathways (or benefit–cost ratios, in parentheses).

Flock-rebuild pathway	Self-replacing Merino			Merino-cross			Self-replacing Maternal	Self-replacing Cleanskin	
	Dual purpose	Wool focussed	Rangeland zone	Merino × Terminal	Merino × BL	BLM × Terminal		Agricultural zone	Rangeland zone
1. Retain older ewes	**$153**	**$161**	**$66**	**(1.4)**	**(1.6)**	**(1.4)**	**$129**	**$131**	**$44**
2. Retain more young ewes	$18	$35	−$6	n/a	n/a	n/a	$16	$17	−$26
3. Buy ewe hoggets	**$115**	**$129**	**$18**	**(1.3)**	**(1.5)**	**(1.3)**	$98	$101	−$2
4. Buy aged ewes	**$92**	**$110**	−$7	**(1.1)**	**(1.2)**	**(1.1)**	$82	$84	−$33
5. Re-join once-dry ewes	**$170**	**$155**	**$85**	**(4.0)**	**(4.1)**	**(4.4)**	**$171**	**$173**	**$102**
6. Increase twin-lamb survival	**$153**	**$105**	**$63**	n/a	n/a	n/a	**$162**	**$164**	**$84**
7. Supplement ewes pre-joining	−$8	$18	−$81	n/a	n/a	n/a	$71	$73	−$45
8. Flushing with lupins for 2 weeks at joining	$22	$31	−$54	n/a	n/a	n/a	**$99**	**$101**	−$10
9. Inject Ovastim pre-joining	**$102**	**$98**	**$19**	n/a	n/a	n/a	**$149**	**$151**	**$51**
10. Join ewe lambs	$78	$59	−$125	n/a	n/a	n/a	**$115**	**$117**	**$21**
11. Accelerated lambing 1: join every 8 months	$1	−$12	−$87	n/a	n/a	n/a	−$36	−$20	−$64
12. Accelerated lambing 2: join every 4 months	$7	−$2	−$70	n/a	n/a	n/a	−$25	−$11	−$130
13. Increase Merino × Merino matings	$24	$40	−$21	**(0.8)**	**(1.0)**	n/a	n/a	n/a	n/a
14. Sexed-semen use	−$335	−$292	−$344	n/a	n/a	n/a	−$253	−$251	−$326

Top six pathways are bolded, unless the NPV/DSE value is negative.
n/a, not applicable.

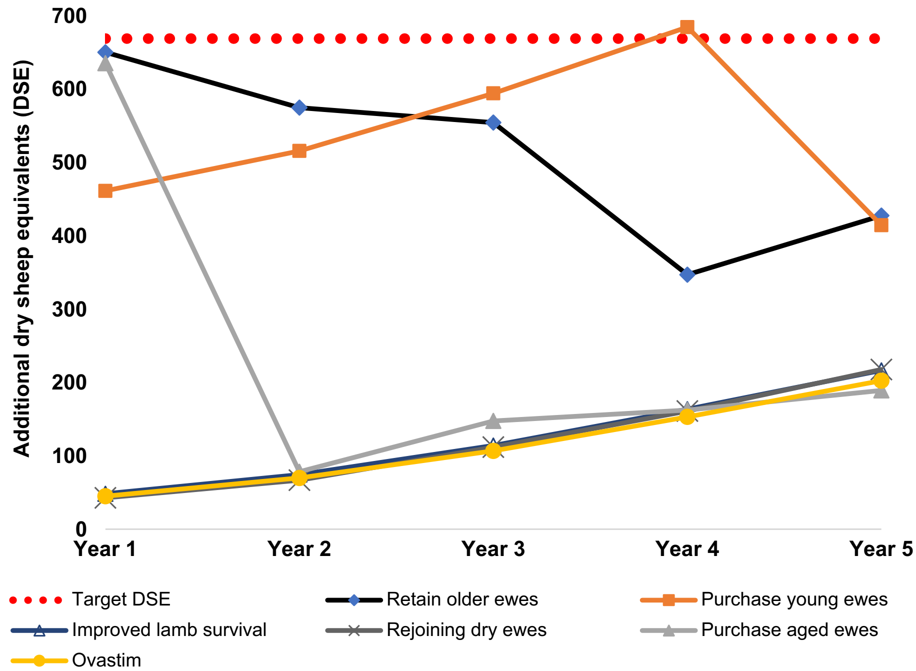

Fig. 1. The number of additional dry sheep equivalents (DSE) generated over 5 years from use of the top six flock-rebuilding pathways for a self-replacing dual-purpose Merino flock. The target DSE of 669 (equivalent to an extra 250 ewes) is the number required to completely restock the property, assumed to be 20% understocked before flock-rebuilding strategies are applied.

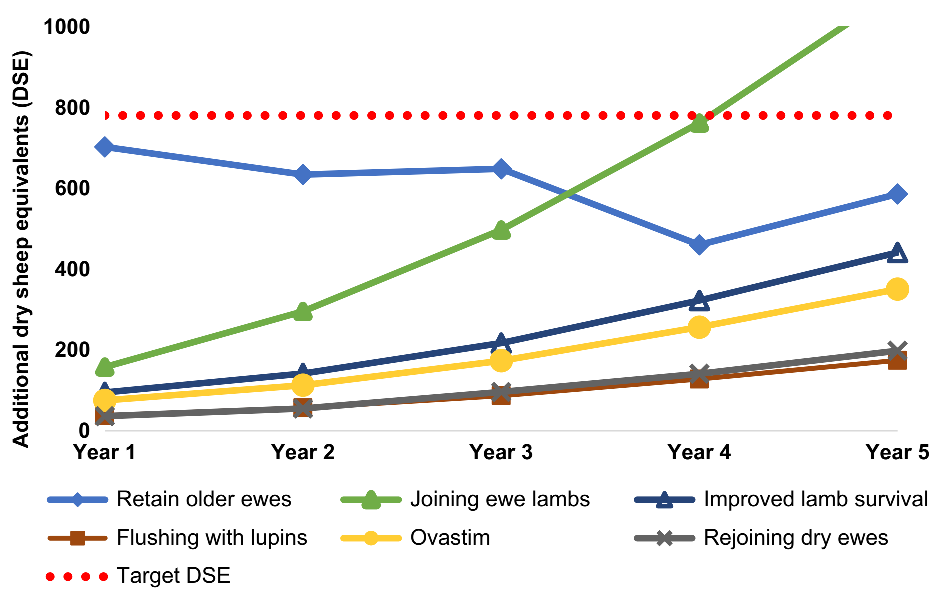

Fig. 2. The number of additional dry sheep equivalents (DSE) generated over 5 years from use of the top six flock-rebuilding pathways for a self-replacing Maternal flock. The target DSE of 780 (equivalent to an extra 250 ewes) is the number required to completely restock the property, assumed to be 20% understocked before flock-rebuilding strategies are applied.

assumed to be 20% understocked before flock-rebuilding strategies are applied.

For a self-replacing dual-purpose Merino flock, implementing the strategies of retaining and purchasing older ewes (Pathways 1 and 4) and purchasing hogget ewes (Pathway 3) have a more immediate effect on increasing the dry sheep equivalents (DSE) being carried than does implementing the remaining three strategies shown. This is a result of more grown sheep (either retained or purchased ewes) being on the property immediately following the strategy being implemented. The effect of strategies to generate more progeny (improving twin-lamb survival and vaccinating ewes with Ovastim) take longer to increase DSE, given the time taken from implementation to allow for mating, pregnancy, lactation and weaning before the progeny start contributing to the DSE counts.

For a self-replacing Maternal flock, the situation with increasing DSEs is similar, with retention of older ewes and purchasing of ewe hoggets resulting in a more rapid increase, with joining ewe lambs quickly building DSEs, so that by Year 4, the DSEs are approaching the property target. Indeed, some reduction in stock numbers would need to be implemented by Year 5 to keep within the DSE target.

Sensitivity of flock-building pathways

Variation in supplementary-feed costs

The sensitivity of flock-rebuilding strategies to variation in supplementary-feed costs (23% lower and 23% higher than the assumed standard price of $260/t) in terms of NPV/DSE values are presented in Table 4 for a self-replacing dual-purpose Merino flock and in Table 5 for a self-replacing Maternal flock

For a self-replacing dual-purpose Merino flock, varying supplementary-feed costs by 23% had little effect on the NPV/DSE value or its rank for the top six flock-rebuilding pathways (1 (retain older ewes), 3 (buy ewe hoggets), 4 (buy aged ewes), 9 (Ovastim injection), 6 (increase of twin-lamb survival) and 5 (re-join once-dry ewes)), except as explained below.

Table 4. Feed-cost sensitivity analysis on net present value/dry sheep equivalent value (A$) and rank for flock-rebuilding pathways for a self-replacing dual-purpose Merino flock.

Flock-rebuild pathway	Low feed cost (A$200/t)	High feed cost (A$320/t)
1. Retain older ewes	**$159**	**$147**
2. Retain more young ewes	$21	$15
3. Buy ewe hoggets	**$121**	**$108**
4. Buy aged ewes	$98	**$85**
5. Re-join once-dry ewes	**$173**	**$167**
6. Increase twin-lamb survival	**$162**	**$144**
7. Supplement ewes pre-joining	$28	−$44
8. Flushing with lupins	$53	−$9
9. Ovastim injection	**$110**	**$94**
10. Join ewe lambs	**$103**	$52
11. Accelerated lambing – Type 1	$31	$13
12. Accelerated lambing – Type 2	$35	$16
13. Increase Merino × Merino matings	$27	$21
14. Sexed-semen use	−$332	−$338

Top six pathways are bolded, unless the NPV/DSE value is negative.

Table 5. Feed-cost sensitivity analysis on net present value/dry sheep equivalent value (A$) and rank for flock-rebuilding pathways for a self-replacing Maternal flock.

Flock-rebuild pathway	Low feed cost (A$200/t)	High feed cost (A$320/t)
1. Retain older ewes	**$134**	**$124**
2. Retain more young ewes	$18	$13
3. Buy ewe hoggets	$104	**$93**
4. Buy aged ewes	$87	$77
5. Re-join once-dry ewes	**$174**	**$169**
6. Increase twin-lamb survival	**$171**	**$153**
7. Supplement ewes pre-joining	$96	$47
8. Flushing with lupins	**$120**	$79
9. Ovastim injection	**$155**	**$143**
10. Join ewe lambs	**$134**	**$95**
11. Accelerated lambing – Type 1	−$27	−$45
12. Accelerated lambing – Type 2	−$16	−$35
13. Increase Merino × Merino matings	n/a	n/a
14. Sexed-semen use	−$250	−$256

Top six pathways are bolded, unless the NPV/DSE value is negative.
n/a, not applicable.

Buying aged ewes (5.5 year-old, Pathway 4), while increasing in profitability as a strategy, with lower supplementary-feed costs, moved down in rank from 6th to 7th, being replaced as one of the top six pathways by Pathway 10 (join ewe lambs), but this was a inconsequential change. Pathway 7 (supplement ewes pre-joining) became profitable at lower supplementary-feed costs, but became more unprofitable when supplementary-feed costs increased by 23%. Other than that, the ranking and NPV/DSE values of other flock-rebuilding strategies that were not in the top six changed little.

For a self-replacing Maternal flock, the top six flock-rebuilding pathways remained the same under a low compared with a standard supplementary feeding-cost assumption. These were Pathways 1 (retain older ewes), 8 (flushing with lupins), 9 (Ovastim injection), 10 (join ewe lambs) and 5 (re-join dry ewes). Under a high feeding-cost assumption, Pathway 3 (buy ewe hoggets) became one of the top six pathways, replacing Pathway 8 (flushing with lupins); other than that, the ranking of the top six pathways did not change with differing supplementary feed-cost assumptions. The absolute NPV/DSE values also changed little. Pathway 7 (supplementing ewes pre-joining) became more attractive with lower supplementary feeding costs, and less so with a higher cost, but maintained profitability. There were no other changes in NPV/DSE values of consequence for the flock-rebuilding pathways as a result of lower or higher supplementary-feeding costs.

Variation in stock prices (includes sale, inventory, purchase and ram values)

The sensitivity of flock-rebuilding pathways to variation in stock prices (20% lower or 20% higher than the assumed standard prices) in terms of NPV/DSE values are presented in Tables 6 and 7 for a self-replacing dual-purpose Merino flock and a self-replacing Maternal flock respectively.

For a self-replacing dual-purpose Merino flock, varying stock prices by 20% had little effect on the rank (based on NPV/DSE value) of flock-rebuilding pathways, with the top six pathways remaining unchanged (as previously listed above when discussing the effect of varying supplementary-feeding costs). However, with 20% lower stock prices, while all are still profitable, the NPV/DSE values for the top six flock-rebuilding pathways were typically reduced by 25–33%, the most affected pathway being Ovastim vaccination (with a decline of 47% in NPV/DSE). Conversely, a 20% increase in stock prices increased the profitability of most flock-rebuilding pathways considered, with the NPV/DSE values for the top six pathways typically increasing by 25–32%.

With 20% higher stock prices (than the prices assumed in the standard model), some flock-rebuilding pathways previously lowly ranked became more profitable. In particular, joining ewe lambs (Pathway 10) became more worthwhile, increasing to 7th in rank, similar to buying aged ewes (Pathway 4), with accelerated lambing systems (Pathways 12 and 13) and supplementing ewes pre-joining to improve ewe condition score (Pathway 7), also assessed as having NPV/DSE values of $40 or better. Also, flushing with lupins (Pathway 8) became more profitable under a high stock-price scenario. However, with the exception of joining ewe lambs (Pathway 10), these strategies became unprofitable if stock prices declined by 20% from their currently assumed values and are therefore assessed as being more unreliable economically to use than are the top six ranked pathways, as well as generally being less profitable, regardless of reigning stock prices. Under all stock-price assumptions, use of sexed semen (Pathway 14), although generating a higher proportion of female progeny, was a distinctly unprofitable flock-rebuilding pathway.

For a self-replacing Maternal flock, again the top six flock-rebuilding pathways remained the same (as previously listed above when discussing the effect of varying supplementary-feeding costs), each with the same rank. At 20% lower stock prices, the top six pathways all remained profitable, but decreased in NPV/DSE by 29–47% compared with the assumed standard prices. However, some lower-ranked flock-rebuilding pathways either became unprofitable (Pathway 2: retain more young ewes) or became more marginal in profitability (Pathway 4: buying aged ewes; and Pathway 7: supplementing ewes pre-joining). At 20% higher stock prices, all except three flock-rebuilding pathways (accelerated lambing systems, Pathways 11 and 12, and Pathway 14: use of sexed semen) became profitable. At 20% higher stock prices, the top six pathways increased in NPV/DSE by 30–47% compared with assumed standard prices.

Table 6. Stock-price sensitivity analysis on net present value/dry sheep equivalent value (A$) and rank for flock-rebuilding pathways for a self-replacing dual-purpose Merino flock.

Flock-rebuild pathway	20% Lower stock prices	20% Higher stock prices
1. Retain older ewes	**$112**	**$194**
2. Retain more young ewes	$9	$27
3. Buy ewe hoggets	**$81**	**$148**
4. Buy aged ewes	**$62**	**$121**
5. Re-join once-dry ewes	**$127**	**$213**
6. Increase twin-lamb survival	**$105**	**$201**
7. Supplementing ewes pre-joining	–$26	$40
8. Flushing with lupins	–$26	$70
9. Ovastim injection	**$54**	**$150**
10. Join ewe lambs	$34	$121
11. Accelerated lambing – Type 1	–$6	$50
12. Accelerated lambing – Type 2	–$4	$56
13. Increase Merino × Merino matings	$13	$35
14. Sexed-semen use	–$329	–$342

Top six pathways are bolded, unless the NPV/DSE value is negative.

Table 7. Stock-price sensitivity analysis on net present value/dry sheep equivalent values (A$) and rank for flock-rebuilding pathways for a self-replacing Maternal flock.

Flock-rebuild pathway	20% Lower stock prices	20% Higher stock prices
1. Retain older ewes	**$78**	**$180**
2. Retain more young ewes	–$2	$33
3. Buy ewe hoggets	**$52**	**$144**
4. Buy aged ewes	$39	$125
5. Re-join once-dry ewes	**$121**	**$222**
6. Increase twin-lamb survival	**$105**	**$219**
7. Supplementing ewes pre-joining	$14	$129
8. Flushing with lupins	$42	**$157**
9. Ovastim injection	**$92**	**$207**
10. Join ewe lambs	**$62**	**$167**
11. Accelerated lambing – Type 1	–$58	–$14
12. Accelerated lambing – Type 2	–$51	$0
13. Increase Merino × Merino matings	n/a	n/a
14. Sexed-semen use	–$257	–$248

Top six pathways are bolded, unless the NPV/DSE value is negative.
n/a, not applicable.

Variation in flock structure

The effect of using an older flock structure (ewes given six annual mating opportunities and culled at 7.5 years of age compared with culling at 5.5 years of age, with only four annual mating opportunities given) on the NPV/DSE of flock-rebuilding pathways and their rank, is documented in Table 8 for a self-replacing dual-purpose Merino flock. A 10% lower lamb marking percentage for adult ewes is assumed in the older flock structure (and 5% lower for maiden ewes). This assumption was made from observations that older flock structures are often associated with lower reproductive performance and a need to carry more ewe age groups to generate sufficient flock replacements after allowing for some culling of ewe lambs and hoggets.

The top six flock-rebuilding pathways remained the top six under an older flock structure. However, the biggest effect of assuming an older age structure is that Pathway 4 (buy old ewes; 5.5-year-old ewes) becomes the most profitable, with Pathway 3 (buy ewe hoggets) becomes less profitable. This is not totally surprising, as ewes purchased at 5.5 years of age can still be bred for 2 years before being culled under an older age structure, whereas they can be bred only for 1 year under the standard flock structure. Other changes in profitability and ranking of flock-rebuilding pathways from changing to an older flock structure are minor. Pathways 2 (retaining more young ewes), and 11 and 12 (accelerated lambing systems) become unprofitable and joining ewe lambs (Pathway 10), while still profitable, becomes less so.

Variation in discount rate

The top six flock-rebuilding pathways remained the top six when the discount rate was increased from 3.5% per annum to 7% per annum (individual values not shown). However, the NPV/DSE values were reduced from a range of A$92–170 to values ranging from A$53 to A$143 for a dual-purpose, self-replacing Merino flock and from a range of A$99–171 to values ranging from A$85 to A$150 for a self-replacing Maternal flock.

Discussion

This study assessed the economic merit of 14 individual flock-rebuilding pathways and the rate that they are able to return a property that is 20% understocked to an optimal stocking capacity within a 5-year timeframe. Assessments were conducted for a number of flock types and regions, to represent the majority of sheep production systems utilised in Australia. Pathways are discussed below under the five categories defined earlier in the paper.

(i) Retain ewes for longer than normal, cull fewer or purchase more

Flock-rebuilding pathways assessed as having good profitability when rebuilding numbers quickly mainly belong to this category. Many Australian sheep producers are retaining more ewes for breeding replacements in the current phase of flock rebuilding that commenced in 2020, by one of or a combination of keeping mature breeding ewes for longer and culling fewer ewe lambs and ewe hoggets than normal, according to a recent survey (MLA 2021). Compared with the assessment of good profitability for retaining older ewes

Table 8. Flock-structure sensitivity analysis on net present value/dry sheep equivalent value (A$) and rank for flock-rebuilding pathways for a self-replacing dual-purpose Merino flock.

Flock-rebuild pathway	Flock structure: dual-purpose Merino flock	
	Standard: 4 ewe age groups 100% lamb marking % for adult ewes 90% for hogget ewes	Older: 6 ewe age groups 90% lamb marking % for adult ewes 85% for hogget ewes
1. Retain older ewes	**$153**	**$157**
2. Retain more young ewes	$18	−$4
3. Buy ewe hoggets	**$115**	**$59**
4. Buy aged ewes	**$92**	**$217**
5. Re-join once-dry ewes	**$170**	**$175**
6. Increase twin-lamb survival	**$153**	**$122**
7. Supplementing ewes pre-joining	−$8	−$17
8. Flushing with lupins	$22	$16
9. Ovastim injection	**$102**	**$103**
10. Join ewe lambs	$78	$37
11. Accelerated lambing – Type 1	$1	−$1
12. Accelerated lambing – Type 2	$7	$5
13. Increase Merino × Merino matings	$24	$10
14. Sexed-semen use	−$335	−$432

Top six strategies are bolded, unless the NPV/DSE value is negative.

(Pathway 1), our results indicated that retention of a higher proportion of young ewes (Pathway 2) is much less profitable, with costs slightly exceeding returns under rangeland conditions for both Merino and particularly Cleanskin flock types.

Purchasing young ewes (Pathway 3) and, to a slighter lesser extent, purchasing aged ewes (Pathway 4) are profitable pathways to rapidly rebuild stock numbers, across most flock types investigated, with some exceptions. While purchasing young Merino ewes in the rangelands is modestly profitable, purchasing older Merino ewes, and young and older Cleanskin ewes are not.

Concerns regarding biosecurity risk (such as the risks of introducing footrot, ovine Johne's disease and gastro-intestinal nematodes resistant to anthelmintics) and uncertainty of the merit of outside genetics (with the risk of lowering the genetic merit of the flock) when purchasing ewes need to be weighed against other flock-rebuilding options when making decisions.

(ii) Reduce wastage by improving fertility and lamb survival

Flock-rebuilding pathways belonging to this category, although assessed as having good profitability, do not have the same immediate flock-rebuilding capacity as do those in Category i. Re-joining once-dry ewes (Pathway 5) had the highest profitability on a NPV/DSE basis across all flock types; however, the actual dry-ewe numbers involved are minor, explaining why the flock-rebuilding capacity is low. Also, the practice may be practical to implement only in situations where the normal joining time is early in the breeding season, such as in late spring and early summer. Otherwise, the re-joining of ewes within the same season results in these ewes lambing down well beyond the optimal lambing time, creating inconvenience for management. Further, the assumptions used for the reproductive performance of once-dry ewes are from flocks mated only annually (Hatcher *et al*. 2018). Data from flocks that re-mate dry ewes within the same breeding season are required to obtain results more representative of the likely re-breeding performance of once-dry ewes when this pathway is utilised.

Increasing twin-lamb survival (Pathway 6) is also profitable on a NPV/DSE basis across all flock types assessed, but again the low numbers of extra replacements generates a low flock-rebuilding capacity. Despite this drawback in terms of flock-rebuilding potential, the practice of customised feeding supplements in late pregnancy to improve twin-lamb survival is profitable, suggesting that it should become standard management practice.

(iii) Boost reproductive potential via increases in ovulation rate

Flock-building pathways that belong to this category are assessed as profitable in several flock types modelled (e.g. Ovastim injection (Pathway 9), flushing ewes with lupins (Pathway 8) and feeding cereal grain supplements pre-joining (Pathway 7)). However, if these options are implemented on farm, it is critical for lamb and ewe survival and productivity that ewe nutrition is tailored to litter size by identifying and separating dry, single and multiple-bearing ewes into different mobs by ultrasound scanning and ensuring that targets for condition score (especially by lambing time) are met (Lifetimewool 2011; Young *et al*. 2016). A higher proportion of treated ewes will be bearing twins (or more) during pregnancy, with twin- and multiple-bearing ewes needing to reach a higher average condition score (of at least three) by lambing time than is the case for ewes bearing single lambs (Hocking-Edwards *et al*. 2011). Furthermore, and similar to Category ii (reduce wastage by improving fertility and lamb survival) flock-rebuilding pathways, Category iii pathways also have only modest capacity to rebuild flock numbers within a 5-year timeframe.

Use of a melatonin implant (marketed as 'Regulin') can also increase reproductive potential, with responses obtained of 19–27% extra lambs born to maiden Merino and mature Border Leicester × Merino ewes given melatonin implants before joining in late spring (Williams *et al*. 1992). A preliminary calculation, on the basis of the results of Williams *et al*. (1992), suggests that using Regulin is likely to perform similarly, in economic terms, to injecting ewes with Ovastim (results not shown).

(iv) Joining at a younger age and joining more than once a year

Joining ewes as lambs (Pathway 10) at approximately 7–10 months of age was assessed as a profitable flock-rebuilding pathway across all self-replacing flock types (except Merinos in the rangelands), ranking in the top six pathways for self-replacing Maternal and Cleanskin flock types. These findings are heavily dependent on achieving minimum weaning rates from ewe lambs of 70% and 50% in Maternal and Cleanskin flock types and Merino flock types respectively.

Achieving consistent reproductive performance from joining ewe lambs from one year to the next has been a challenge for sheep producers in New Zealand and Australia and has had limited adoption in the past, especially in Merino flocks (Kenyon *et al*. 2014). Despite that, average weaning rates of 76.9% over 8 years have been reported recently from joining of composite ewe lambs on two commercial properties in south-eastern Australia (Thompson *et al*. 2021). In another study summarising data from 22 commercial and research farms across Australia, fetuses scanned per 100 ewe lambs mated at 7–10 months of age (over 1–8 years) averaged 60.7% in 11 flocks joining Merino ewe lambs and 96.9% in five flocks joining Maternal ewe lambs (A. Thompson, pers. comm.).

Joining ewe lambs also has the benefit of being able to steadily rebuild flock numbers at a greater rate than

Category ii (reduce wastage by improving fertility and lamb survival) and Category iii (boost reproductive potential via increases in ovulation rate) flock-rebuilding pathways, although not as rapidly as Category i (retain ewes for longer than normal, cull fewer or purchase more) pathways. This is partly because the ewe lambs are already available on the property and there is no lengthy delay breeding extra ewes for mating.

Our results indicated that joining ewes more than once a year (accelerated lambing) is only marginally profitable, at best, as a flock-rebuilding pathway. In the absence of published and detailed costs of implementation, we assumed that large amounts of supplementary feeding, plus other additional management costs, would be necessary to sustain accelerated lambing systems, especially when breeding out of season. The total extra cost assumed is A$45.66–53.95 per ewe each year (see Supplementary Tables S9 and S10 for detailed assumptions). Potential refinement of supplementary feeding and management systems may assist in reducing some of these costs, with improved animal performance also helping further defray them, thereby increasing profit. However, accelerated lambing systems are likely to remain high-cost systems under Australian conditions, with little margin available for use of pharmacological interventions to breed ewes outside of their normal breeding season. Indeed, both Smith *et al.* (2012) and Fogarty and Mulholland (2013) stressed the importance for cost-effectiveness of using suitable genotypes and systems that do not rely on artificial-breeding technologies and drugs.

The predicted effects on stock numbers (reported as DSEs) of using accelerated lambing systems suggest that the modelled property is immediately at or above its optimal stocking-rate target as soon as the systems are implemented. This is non-sensical. Only in the second round of matings should stocking rates start to increase above those predicted for an annual mating system. Refinements in the methodology are required to better predict DSEs from use of accelerated lambing systems, especially in the initial implementation phase.

(v) Other pathways

Mating a higher proportion of Merino ewes to Merino rams in self-replacing flocks (Pathway 13) to increase pure Merino ewe replacements is modestly profitable in dual-purpose Merino and wool-focussed Merino flock types, but not for Merinos in the rangelands. This suggests that although alternative pathways may be more profitable, Merino sheep producers (except in the rangelands) can economically use this pathway to contribute towards the rebuilding of the pure Merino ewe base at an industry level.

The use of sexed-semen to breed only females is highly unprofitable in a commercial flock setting, regardless of flock type. The high cost of performing artificial insemination, not normally practiced in a commercial flock setting, is a necessary component of using sexed semen. In a flock already practicing artificial insemination with higher-value animals involved in genetic improvement programs, use of sexed semen may be more economically feasible.

Implementing one or more of these rebuilding pathways, with the intention of returning a property back to an optimal stocking rate, did not require scaling back an ongoing alternative enterprise, as the assumption was that, at the outset, the modelled property was 20% understocked. As stated earlier, the economic benefits of two alternatives to flock rebuilding of utilising excess feed through agistment or the making and sale of hay were evaluated but were calculated to be less profitable than the top six flock-rebuilding pathways.

Sensitivity of flock-building pathways

The general findings are that the profitability of flock-rebuilding pathways improve with lower supplementary-feed costs or higher stock prices and decline with an increase in supplementary-feed costs and discount rates or lower stock prices. Further, the relative ranking of the profitability of each of the flock-rebuilding pathways is little changed with variations in feed costs or stock prices. However, these findings assume modest changes of 20–23% in costs and prices that, nonetheless, are considered within the scope of potential changes in the foreseeable future. Further, the top six flock-rebuilding pathways remained the top six with a much higher discount rate of 7% per annum rather than the 3.5% per annum discount rate assumed in our study.

Of note is that some flock-rebuilding pathways (including supplementing ewes pre-joining (Pathway 7), flushing with lupins (Pathway 8), and accelerated lambing systems (Pathways 11 and 12) identified as marginally profitable for the dual-purpose Merino flock type reliant on standard supplementary feed-cost and stock-price assumptions become quite profitable when supplementary-feed costs are lower or stock prices are higher. As stock prices have recently increased above even the high prices assumed in our study (completed in June 2021), these favourable circumstances may provide an opportunity for some sheep producers to profitably trial less traditional methods of flock rebuilding (such as accelerated lambing, joining ewe lambs and feeding supplements at joining to increase ovulation rates), especially if they are concerned about the biosecurity risk of purchasing ewes.

We found little sensitivity in profit and rank of flock-rebuilding pathways when investigating a change to an older flock structure for a self-replacing dual-purpose Merino flock type. Nonetheless, buying aged ewes at 5½ years of age became the most profitable pathway for flock rebuilding when breeding ewes could be retained for an additional 2 years in the flock. However, although not specifically investigated, achieving a higher weaning rate, rather than permanently retaining an older-ewe flock structure, may be a more profitable option in the broader sense of assessing whole-farm returns (Tables 9, 10).

Table 9. Discount-rate sensitivity analysis on net present value/dry sheep equivalent value (A$) and rank for flock-rebuilding pathways for a self-replacing dual-purpose Merino flock.

Flock-rebuild pathway	Discount rate 7% per annum
1. Retain older ewes	**$130**
2. Retain more young ewes	$3
3. Buy ewe hoggets	**$83**
4. Buy aged ewes	**$61**
5. Re-join once-dry ewes	**$148**
6. Increase twin-lamb survival	**$133**
7. Supplementing ewes pre-joining	–$13
8. Flushing with lupins	$14
9. Ovastim injection	**$87**
10. Join ewe lambs	$64
11. Accelerated lambing – Type 1	$17
12. Accelerated lambing – Type 2	$19
13. Increase Merino × Merino matings	$12
14. Sexed-semen use	–$329

Top six pathways are bolded, unless the NPV/DSE value is negative.

Table 10. Discount-rate sensitivity analysis on net present value/dry sheep equivalent value (A$) and rank for flock-rebuilding pathways for a self-replacing Maternal flock.

Flock-rebuild pathway	Discount rate 7% per annum
1. Retain older ewes	**$109**
2. Retain more young ewes	$2
3. Buy ewe hoggets	$72
4. Buy aged ewes	$57
5. Re-join once-dry ewes	**$150**
6. Increase twin-lamb survival	**$141**
7. Supplement ewes pre-joining	$59
8. Flushing with lupins	**$85**
9. Ovastim injection	**$130**
10. Join ewe lambs	**$97**
11. Accelerated lambing – Type 1	–$36
12. Accelerated lambing – Type 2	–$27
13. Increase Merino × Merino matings	n/a
14. Sexed-semen use	–$247

Top six pathways are bolded, unless the NPV/DSE value is negative.
n/a, not applicable.

Conclusions

This study has provided a strong platform for assessing the economic merits of a range of flock-rebuilding pathways across the main flock types and sheep-producing zones in Australia. These assessments are based on performance and cost assumptions typical for the flock types and zones considered. However, individual flock performances and cost structures may vary from our assumptions and need to be considered when making decisions on flock-rebuilding pathways for specific situations. In that regard, 'ImPack', a module of the StockPlan suite of programs developed by the New South Wales Department of Primary Industries (McPhee *et al.* 2010) to explore the consequences of a drought-forced reduction in stock numbers and recovery to pre-drought levels for individual property circumstances, is currently being updated (but was not available at the time of writing this paper).

The flock-rebuilding pathways assessed as being more or highly profitable and that rebuilding flock numbers quickly mainly belong to Category i (retain ewes longer than normal, cull fewer and purchase more), with the possible exception of joining ewe lambs (Pathway 10). The simplicity and ease of implementing these more profitable options, particularly retaining ewes for longer, are reasons why they are already widely adopted within the Australian sheep industry.

Despite current high stock prices, purchasing ewes, particularly young ewes, can be a profitable strategy to rapidly rebuild stock numbers. Sheep producers that do not regularly purchase replacements (apart from rams) may be understandably concerned about the biosecurity risk, the cash-flow implications and the uncertainty of the genetic merit of purchased ewes. These concerns need careful consideration and weighing against other flock-rebuilding options, which is one of the ways the outputs of this study can facilitate sheep producers' decision-making.

Other flock-rebuilding pathways that 'reduce wastage by improving fertility and lamb survival', although profitable, do not have the same immediate capacity to rapidly rebuild flock numbers as do the previously mentioned pathways. Also, more meaningful data are required to make confident assumptions on the breeding performance of once-dry ewes (as assessed by ultrasound pregnancy scanning) that are mated for a second time within the same breeding season.

Some of the flock-building pathways that 'boost reproductive potential via increases in ovulation rate' also can be profitable. However, we believe that before these pathways are considered, the fundamental recommendations around ewe condition score at joining, nutrition during joining and late pregnancy, ewe condition score pre-lambing, and lamb survival (singles at 90% and twins at 70–75%) need to be met first.

Joining ewe lambs, if adopted with appropriate management inputs, can be a profitable pathway to rapidly rebuild flock numbers, especially in Maternal and Cleanskin flocks. In the past, few sheep producers joined ewe lambs, but adoption and experience of the practice has been growing steadily in recent years and represents another tool for rapid flock rebuilding that does not require purchasing extra ewes.

Joining ewes more than once a year in accelerated lambing systems is marginally profitable or slightly unprofitable as a flock-rebuilding pathway, depending on the flock type. However, refinements to feeding lambs, particularly those born out of season and general improvement in the management of ewes and lambs in accelerated lambing systems may provide sufficient scope to enable profits to be made by sheep producers willing to trial these techniques. The flock-rebuilding capacity of accelerated lambing systems is high compared with other pathways.

Finally, although this study examined flock-rebuilding pathways for understocked properties in recovery from periods of drought and for other reasons, the findings are also applicable to sheep producers expanding their flocks to fully stock either newly purchased or leased land.

Supplementary material

Supplementary material is available online.

References

ABS (1991) 'Catalogue no. 7111.0. Agricultural Committees, Australia 1888/89.' (Australian Bureau of Statistics: Canberra, ACT, Australia)

ABS (1996) Catalogue 7215.0. Livestock Products, Australia, January 1996, Australian Bureau of Statistics. Available at https://www.ausstats.abs.gov.au/ausstats/free.nsf/0/DE7CCC71E2513A88CA257225000739F3/$File/72150_0196.pdf [Verified 21 January 2022]

ABS (2021*a*) Agricultural commodities, Australia. Available at https://www.abs.gov.au/statistics/industry/agriculture/agricultural-commodities-australia/latest-release [Verified 9 December 2021]

ABS (2021*b*) Livestock Products, Australia. Available at https://www.abs.gov.au/statistics/industry/agriculture/livestock-products-australia [Verified 22 January 2022]

Allworth MB, Wrigley HA, Cowling A (2017) Fetal and lamb losses from pregnancy scanning to lamb marking in commercial sheep flocks in southern New South Wales. *Animal Production Science* **57**, 2060–2065. doi:10.1071/AN16166

Brien FD, Cumming IA, Baxter RW (1977) Effect of feeding a lupin grain supplement on reproductive-performance of maiden and mature ewes. *Journal of Agricultural Science* **89**, 437–443. doi:10.1017/S0021859600028367

Brien FD, Hinch GN, van der Werf JHJ, Brown DJ, Swan AA (2011) Selection strategies for the genetic improvement of reproductive performance in sheep. In '19th Conference of the Association for the Advancement of Animal Breeding and Genetics', Perth, WA, Australia, 19–21 July 2011. pp. 151–158. (Association for the Advancement of Animal Breeding and Genetics (AAABG): Armidale, NSW, Australia)

Croker KP, Johns MA, Johnson TJ (1985) Reproductive performance of Merino ewes supplemented with sweet lupin seed in southern Western-Australia. *Australian Journal of Experimental Agriculture* **25**, 21–26. doi:10.1071/EA9850021

Fogarty NM, Mulholland JG (2013) Annual lambing performance of crossbred ewes in out-of-season and accelerated lamb production systems. *Animal Production Science* **53**, 1093–1100. doi:10.1071/AN12269

Fowler DG (2007) 'Lamb marking performance for ultrasound-scanned ewes in Australian sheep flocks. Project AHW.131.' (Meat and Livestock Australia: Sydney, NSW, Australia)

Gaunt G, Schelfhorst E, Dunstan M (2017) Participatory research evaluating and demonstrating the impact of green feed (particularly lucerne) on sheep conception. Final report to Meat and Livestock Australia for Project B.LSM.0053. Meat and Livestock Australia, Sydney, NSW, Australia. Available at https://www.mla.com.au/contentassets/3bb1a73e50ee4be4b80d673880467232/b.lsm.0053_final_report.docx.pdf [verified 23 November 2021]

Geldard H, Dow GJ, Scaramuzzi RJ, Hoskinson RM, Cox RI, Beels CM (1984) Immunization of ewes with polyandroalbumin to improve fecundity. *Australian Veterinary Journal* **61**, 130–132. doi:10.1111/j.1751-0813.1984.tb07212.x

Hatcher S, Dominik S, Richards JS, Young J, Smith J, Tearle R, Brien FD, Hermann N (2018) Ewe culling and retention strategies to increase reproductive rates in Merino sheep. *Animal Production Science* **58**, 1545–1551. doi:10.1071/AN17813

Heape W (1899) Abortion, barrenness and fertility in sheep. *Journal of the Royal Agricultural Society* **60**, 217–248.

Hinch GN, Brien F (2014) Lamb survival in Australian flocks: a review. *Animal Production Science* **54**, 656–666. doi:10.1071/AN13236

Hocking-Edwards JE, Copping KJ, Thompson AN (2011) Managing the nutrition of twin-bearing ewes during pregnancy using Lifetimewool recommendations increases production of twin lambs. *Animal Production Science* **51**, 813–820. doi:10.1071/AN09158

Kenyon PR, Thompson AN, Morris ST (2014) Breeding ewe lambs successfully to improve lifetime performance. *Small Ruminant Research* **118**, 2–15. doi:10.1016/j.smallrumres.2013.12.022

Kleemann DO, Walker SK (2005) Fertility in South Australian commercial Merino flocks: sources of reproductive wastage. *Theriogenology* **63**, 2075–2088. doi:10.1016/j.theriogenology.2004.06.017

Knight TW, Oldham CM, Lindsay DR (1975) Studies in ovine infertility in agricultural regions in Western Australia: the influence of a supplement of lupins (*Lupinus angustifolius* cv. Uniwhite) at joining on the reproductive performance of ewes. *Australian Journal of Agricultural Research* **26**, 567–575. doi:10.1071/AR9750567

Lee GJ, Atkins KD (1996) Prediction of lifetime reproductive performance of Australian Merino ewes from reproductive performance in early life. *Australian Journal of Experimental Agriculture* **36**, 123–128. doi:10.1071/EA9960123

Lewis RM, Notter DR, Hogue DE, Magee BH (1996) Ewe fertility in the STAR accelerated lambing system. *Journal of Animal Science* **74**, 1511–1522. doi:10.2527/1996.7471511x

Lifetimewool (2011) Lifetimewool. Available at http://www.lifetimewool.com.au [Verified 16 May 2023]

Malcolm B, Makeham JP, Wright V (2005) 'The farming game: agricultural management and marketing.' 2nd edn. (Cambridge University Press: Melbourne, Vic., Australia)

McPhee MJ, Whelan MB, Davies BL, Meaker GP, Graham P, Carberry PM (2010) A workshop and software package to reduce environmental and financial impacts – StockPlan. *Environmental Modelling & Software* **25**, 1477–1478. doi:10.1016/j.envsoft.2009.01.006

MLA (2021) Industry Projections 2021. Australian sheep: October update. Available at https://www.mla.com.au/globalassets/mla-corporate/about-mla/documents/mla_october-update-australian-sheep-industry-projections-071021.pdf [Verified 7 December 2021]

Nottle MB, Kleemann DO, Grosser TI, Seamark RF (1997) Evaluation of a nutritional strategy to increase ovulation rate in Merino ewes mated in late spring-early summer. *Animal Reproduction Science* **47**, 255–261. doi:10.1016/S0378-4320(97)00025-0

Smith DH, Jaensch KS, Rutley DL, Brien FD (2012) Performance of Merino ewes in an accelerated lambing system. In 'Animal Production in Australia. The Proceedings of the 29th Biennial Conference of the Australian Society of Animal Production' (Eds. MA Friend, GL Krebs), vol. 29, p. 50. (Australian Society of Animal Production (ASAP), now the Australian Association of Animal Sciences (AAAS), Orange East, NSW, Australia)

Swan AA, van der Werf JHJ, Atkins KD (2007) Developments in breeding objectives for the Australian sheep industry. In '17th Conference of the Association for the Advancement of Animal Breeding and Genetics, Armidale, NSW, Australia, 23–26 September 2007. pp. 483–490. (Association for the Advancement of Animal Breeding and Genetics (AAABG): Armidale, NSW, Australia)

Thompson AN, Bowen E, Keiller J, Pegler D, Kearney G, Rosales-Nieto CA (2021) The number of offspring weaned from ewe lambs is affected differently by liveweight and age at breeding. *Animals* **11**, 2733. doi:10.3390/ani11092733

Williams AH, Mcphee SR, Reeve JL, Staples LD (1992) Optimum use of subcutaneous melatonin implants to enhance the reproductive performance of seasonal and non-seasonal sheep joined in spring and early summer. *Animal Reproduction Science* **30**, 225–258. doi:10.1016/0378-4320(92)90012-3

Young JM, Behrendt R, Curnow M, Oldham CM, Thompson AN (2016) Economic value of pregnancy scanning and optimum nutritional management of dry, single- and twin-bearing Merino ewes. *Animal Production Science* **56**, 669–678. doi:10.1071/AN15202

Data availability. The data from which the results were generated for this paper are available from the corresponding/first author, Forbes Brien. Note that a considerable number of assumptions have been provided in the Supplementary material.

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