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Harvesting subterranean clover seed – current practices, technology and issues

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Abstract. Subterranean clover (*Trifolium subterraneum* L.) is Australia's most widely sown annual pasture legume. Its widespread use as a pasture plant requires a well-functioning seed production industry, and Australia is the only significant producer of subterranean clover seed globally. However, the sustainability of this industry is under threat due to its reliance on ageing harvest equipment and the resultant environmental impacts. In order to evaluate seed harvesting practices, technology, and issues, we report on case studies, workshops, and a survey of seed producers across southern Australia. The Horwood Bagshaw Clover Harvester, designed in the 1950s, remains the most popular subterranean clover seed harvester. We discuss its use and modifications, and document several contemporary issues facing the seed production industry. Issues are primarily soil erosion and degradation; the expensive, slow and labour-intensive harvest process; and poor reliability and maintainability of harvesters that are now at least 30 years old. We conclude the root cause of these issues is the suction harvest technology utilised by the Horwood Bagshaw Clover Harvester. Analysis of the current harvest system is provided to support the development of new approaches to harvest subterranean clover seeds.

Keywords: clover, seed production, pasture systems, soil degradation, sustainable farming systems, erosion, Horwood Bagshaw Clover Harvester.

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Introduction

Subterranean clover (*Trifolium subterraneum* L.) is Australia's most widely sown (over 29 M ha) annual pasture legume (Nichols *et al*. 2012). Over the last century, together with the use of superphosphate, subterranean clover has led to increases in soil fertility and productivity, enabling greater animal production and crop yields (Donald and Williams 1954; Puckridge and French 1983; Smith 2000; Peoples and Baldock 2001). Subterranean clover is integral to the 'ley farming' system developed in Australia, which among other benefits, supplies significant amounts of organic nitrogen (N) to the soil (Puckridge and French 1983; Peoples and Baldock 2001). The N fixed by pasture legumes saves Australian farmers ~$5 billion per year in inorganic fertiliser costs (Reed 2014), but beyond these economic benefits the substitution of synthetic fertilisers with N fixing legumes is important globally as a component of sustainable intensification (Pretty *et al*. 2018).

Widespread use of subterranean clover as a pasture plant requires a well-functioning commercial seed industry. Australia is the only country to develop a significant subterranean clover seed industry, and subterranean clover seed is an important export (Porqueddu *et al*. 2016). The quantity of certified subterranean clover seed produced annually in Australia has ranged between 1000 and 2000 tons in the past 10 years (Australian Seeds Authority 2020*b*), with a similar amount of uncertified seed also produced (Holland 2012). The current number of subterranean clover seed producers is unknown, but is relatively low. Hassall and Associates (2001) estimated 114 certified seed producers, in addition to those producing uncertified seed. However, the area registered for certified subterranean clover seed production has decreased from a recent high of 7041 ha in 2005 to 2525 ha in 2019 (Australian Seeds Authority 2020*a*), suggesting the number of subterranean clover seed producers has decreased further.

Harvesting subterranean clover seed has its inherent challenges; the two most widely sown subspecies (ssp. *subterraneum* and *yanninicum*) bury their seed-bearing burrs. Seed burial is a major factor in the agronomic success of subterranean clover because it reduces seed predation by

Fig. 1. Horwood Bagshaw Clover Harvester operating in a subterranean clover paddock, 2020.

livestock (Nichols *et al.* 2012). However, seed burial prevents the use of conventional harvest equipment, as such harvesters are unable to effectively pick up burrs from the soil. This challenge spurred the invention of novel machinery and many innovative harvesting solutions were developed to harvest and process the seeds, such as sheepskin rollers, which utilise the natural ability of burrs to attach to wool (Quick 2007). Of these machines, the Horwood Bagshaw Clover Harvester – or 'HB' – has been the most significant and enduring (Boyle 1995; Avery *et al.* 2001; Moss *et al.* in press). Shown in Fig. 1, the HB uses suction to pick up material from the soil surface in order to collect and process burrs. Although produced from 1962, it did not undergo any significant design changes before going out of production in the early 1990s (Boyle 1995).

Harvesting with the HB takes place during summer, when conditions are hot and dry. By this time the plants have senesced, which allows the burrs to separate easily from the plant (Avery *et al.* 2001). Prior to harvesting with the HB, the paddock is prepared to bring the burrs to the surface. This involves multiple passes using various cultivation techniques, such as raking and harrowing, and contributes to soil structure degradation (Hassall and Associates 2001). The HB then sucks up burr, soil, and other plant matter through a pickup duct at the rear of the machine, where it is threshed and processed to remove foreign material before delivering seed to a storage bin. This process is depicted in Fig. 2.

The invention of the HB represented a significant advancement in harvest technology, quickly replacing earlier innovations (Moss *et al.* in press). This suction-based harvest method is effective and has been the industry leader for the past 60 years. However, commercial subterranean clover seed production faces several reported issues.

(1) The harvest process can result in soil degradation and erosion (Avery *et al.* 2001; Loi *et al.* 2005).
(2) Although effective at recovering burr, the slow, labour-intensive harvest process also incurs higher production costs than the harvesting of other agricultural crop species (Avery *et al.* 2001; Hassall and Associates 2001; Loi *et al.* 2005).
(3) Harvest machinery is no longer commercially produced or supported (H. Bagshaw, pers. comm.).

Environmental and productivity challenges are threatening the economic viability and sustainability of subterranean

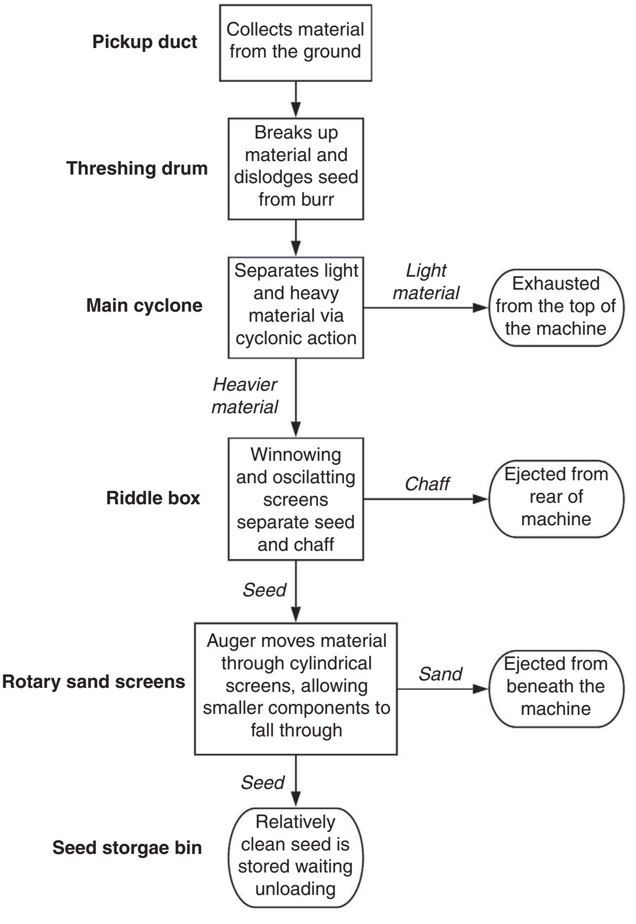

Fig. 2. Flow diagram of the major processes during operation of the Horwood Bagshaw Clover Harvester.

clover seed production (Avery *et al.* 2001; Loi *et al.* 2005). However, seed production issues are not well documented, and efforts to address them are hindered by a lack of recent studies of harvesting practices and equipment. Avery *et al.* (2001) reported there had been little research in this area in the four decades before their report and the limited research since then has focussed on the agronomic, and not the mechanical, aspects of seed production. Hassall and Associates (2001) reported that seed producers believe that the improvement of harvest technologies to minimise or avoid soil damage should be a top priority of the industry. However, the pasture seed market is reported to be too small for the agricultural machinery manufacturer industry to expend large amounts of capital to develop new technology (Hassall and Associates 2001).

This paper evaluates the practices, equipment and issues of current subterranean clover seed producers across Australia and, thereby, explores the hypothesis that harvest technology is the root cause of the key problems affecting the industry: soil degradation, expensive seed production and a decreasing number of seed producers. An improved understanding of harvest practices and associated problems will permit future work to explore alternative harvest systems and develop new technology to upgrade or replace the aging HB.

Materials and methods

Three approaches were taken to document current subterranean clover seed production practices in Australia: (1) on-farm case studies; (2) seed industry workshops; and (3) a survey of seed producers.

On-farm case studies and workshops were conducted in the major seed producing regions of Western Australia (WA), South Australia (SA), New South Wales (NSW) and Victoria (Vic.). Both approaches facilitated engagement with seed producers and helped collect information relating to their practices. The information gathered from these interactions helped form questions for a more detailed survey of seed producers. These approaches were designed to elucidate seed production practices, harvest equipment and issues. Information on annual medic (*Medicago* spp.) seed production was also collected, but will not be presented in this paper. Human ethics approval for the case studies, workshops and survey were obtained from The University of Western Australia (Ref. RA/4/20/5383).

On-farm case studies

Six case studies were conducted on subterranean clover seed producers across Australia: two in each of WA, NSW, and SA. Each was identified as a dedicated, rather than opportunistic, seed producer, and were considered by the research team to be a representative example of best practice in their district. Seed producers were selected in consultation with seed companies and through personal industry contacts of the research team. Field visits were undertaken in February and March 2019 to coincide with the harvest season. Harvest operations were observed and the seed producers interviewed by the research team to understand their harvest process and history, machinery use and modifications, soil erosion impact and mitigation, and issues experienced with harvest processes and machinery.

Seed industry workshops

In March 2019, day-long workshops were conducted in the important pasture seed production districts of Naracoorte SA, Pingelly WA, and Corowa NSW. Workshop participants included pasture seed producers, seed company production managers, agronomists, consultants to the seed industry, and members of rural industry research and development corporations. Approximately 80 attendees were present across the three events. Although the workshops were open to the broader seed industry, they were targeted specifically at seed producers in order to gather information about their harvest experiences and collect input for the development of new harvesting technology. These workshops provided the opportunity to document harvesting practices and issues from a range of seed producers and districts.

Seed producer survey

Informed by the workshops and case studies, a survey was designed and distributed to subterranean clover and annual medic seed producers in Australia. The survey captured information on seed harvesting practices, equipment, and issues through a similar approach to Masarei *et al*. (2019), which surveyed practitioner experiences and equipment in native seed restoration and identified limitations in direct seeding machinery. Survey details are provided in the Supplementary material.

The survey was conducted online, and all responses were collected anonymously. The link to the survey was distributed via email to seed companies and district grower groups, who disseminated it to seed producers in their networks. The survey was also sent to attendees of the seed industry workshops who registered their interest in being surveyed. Companies and participants were encouraged to forward the survey to relevant producers who had not been contacted. This blanket distribution method was used because of the small size and fragmentation of the industry, in an effort to maximise the number of responses. Due to the nature of this distribution method the total number of survey recipients is unknown, and therefore the response rate cannot be estimated.

Survey participants were asked a series of questions about their seed harvesting practices and equipment as well as the limitations, advantages and issues they perceived with their current harvesting system. Harvesting practice questions sought details of the processes taken during paddock preparation, the harvesting process, and post-harvest erosion control. Questions regarding equipment investigated how producers' HBs were used and the nature of any modifications they had made to the standard machine. Information was also gathered on any alternative harvesting processes to the use of HB harvesters. General demographic questions were also asked to establish the context of their farming activities (e.g. post code, soil type, annual average rainfall and access to irrigation). A combination of multiple choice, quantitative and qualitative text-based questions were used. All questions were optional, hence not all respondents completed every question.

Descriptive statistics were used to analyse and interpret the collected data. Qualitative questions were grouped and coded where appropriate to be represented in the dataset. Response statistics are reported as a percentage of the total number of responses to that question (denoted as 'n').

Results

Case studies

A summary of the farming system and harvest procedure for each case study is presented in Table 1. The techniques

Table 1. Details of the harvest procedure for each of the six case studies

	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
Farm details						
State	NSW	NSW	WA	WA	SA	SA
Soil type	Red brown - grey clay	Heavy clay	Sand	Sandy loam	Sandy loam over clay	Sandy loam
Annual average rainfall (mm)[A]	547	689	861	417	508	508
Irrigation	Majority irrigated	Rainfed	Rainfed	Rainfed	Majority irrigated	Irrigated and rainfed
Harvest procedure[B]						
Residue reduction	Rake and bale	Rake and bale	Cattle graze	Sheep graze	Windrow	Rake and bale
Pre-suction preparation	Heavy diamond harrows	Harrow	Power harrow	Harrow	Harrow	Prickle chain
		Inline rake	Chain link harrow	Light harrow	Rake	Inline rake
				Chain harrow		Harrow Chain mesh
Suction harvest passes	2	2	1	1	2–3	2–3
HB harvest units	2 trains[C] of 5 HBs	1 train of 4 HBs	1 train of 2 HBs	2 trains of 2 HBs	2 trains of 3 HBs	3 trains of 3 HBs
Post-harvest treatment	Scarify with airseeder	Airseeder – sow wheat or oats	None	Scarify	Rainfed – scarify	Year 1: Scarify with airseeder
		Paper waste covering every 5th year			Irrigated – sow oats/barley	Year 2: Airseeder – sow oats

[A]Data from the Bureau of Meteorology for the closest weather station for 1980 to 2019.
[B]Each preparation step may be repeated multiple times depending on cultivar and conditions.
[C]A train refers to multiple harvesters behind a single tractor, e.g. '2 trains of 3 HBs' refers to 3 HBs behind a single tractor, with 2 tractors operating at once (6 HBs in operation).

Fig. 3. Location of each survey respondent (from postcode supplied).

and equipment for each stage vary between producers (e.g. different combinations of raking or harrowing), but the purposes behind the operations are consistent. Different variants of equipment are utilised depending on synergies with other farming activities (e.g. hay producers may use a tedder rake because it is already available). The number of HBs used and their configurations depend on the equipment available to the producer and the size of their operation. The techniques used for post-harvest erosion depend primarily on the equipment available and soil type.

Survey

A total of 18 survey responses were received from WA ($n = 3$), SA ($n = 8$), Victoria ($n = 2$) and NSW ($n = 5$), with 16 currently active, and 2 retired. The location of each respondent is shown in Fig. 3. The majority of responses were from the Naracoorte region, an important seed production area in SA.

Harvest process

The harvest process captured from the survey, case studies, and workshops depicts a procedure that is time, labour, and equipment intensive, while also damaging to the soil structure. Although harvest procedures varied among producers and locations, there was a common harvesting structure consisting of four stages: (1) pre-harvest plant residue reduction; (2) pre-suction soil preparation; (3) suction harvesting; and (4) post-harvest soil treatment to reduce erosion.

The flow diagram in Fig. 4 depicts these four stages, together with information on each stage from survey data, Table 2. A high number (median of 11) of total passes is required in the harvest process.

Pre-harvest plant residue reduction aims to remove excess senesced biomass in order to decrease the amount of plant material to be picked up and enable buried burrs to subsequently be brought to the surface. The subsequent pre-suction steps are intended to prepare the plant and paddock so that the seed can be effectively harvested by the HB. Multiple machinery passes loosen the soil surface, bring the buried burrs to the surface and level the ground. Heavy implements (harrows and rakes) break up plant material and separate burr from the vine, followed by lighter implements (chain mesh) to position burrs on the surface in preparation for suction harvesting. Producers recognise these preparation activities degrade the soil structure and remove protective plant cover, leaving the paddock at particular risk of erosion. As such, common best practice is to only prepare areas that will be completed in the same day (harvested and erosion control applied) in order to minimise the area of exposed land.

Suction harvesting is conducted as soon as possible after preparation to reduce the time before erosion control is applied. Multiple suction passes are usually employed to maximise seed capture. The majority of survey respondents (66%, $n = 15$) typically complete two suction passes and high seed yielding paddocks sometimes warrant up to three passes. Producers view the decision to complete additional harvest passes as a trade-off between potential seed gain and the costs of time, wear on equipment, labour, and soil damage.

Preparation tasks are repeated between suction passes to ready the paddock for further harvesting. Raking, harrowing, chain mesh and similar are used between suction passes to bring up more burr and prepare the surface.

Post-harvest erosion control is required as the harvesting process leaves the soil bare, loose, and prone to subsequent wind or water erosion (Fig. 5). All survey respondents (100%,

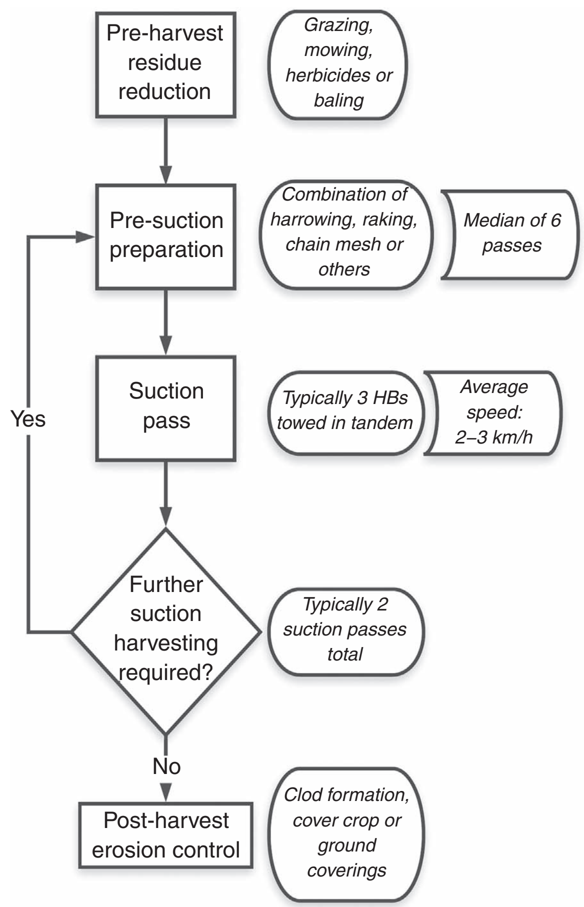

Fig. 4. Flow diagram of typical subterranean clover seed harvest process as ascertained from the survey data.

Table 2. Equipment and methods employed in the four stages of the harvest process

The percentage indicates the proportion of survey respondents utilising the corresponding harvest method for that respective stage. Seed producers can utilise multiple approaches in each stage and therefore method columns sum to over 100%. The number of passes performed for each pre-suction preparation activity is also shown, with statistics for median and range. Note the number of passes is for initial preparation before suction harvesting and do not include subsequent preparation activities between suction harvesting passes

Pre-harvest plant residue reduction ($n = 15$)		Pre-suction soil preparation ($n = 15$)				Seed harvesting ($n = 18$)		Post-harvest erosion control ($n = 15$)	
Method	(%)	Method	(%)	No. passes		Method	(%)	Method	(%)
				Median	Range				
Hay baling	73	Harrowing	100	3	2–8	HB Clover Harvester	100	Clod formation	73
Raking	67	Raking	79	2	1–4	Conventional crop harvester	11	Crop sown	47
Harrowing	60	Chain mesh	40	2	1–4	Custom built harvester	6	Irrigation	13
Grazing animals	40	Total no. passes	–	6	3–14			Straw covering	13
Mowing	40								
Herbicides	20								

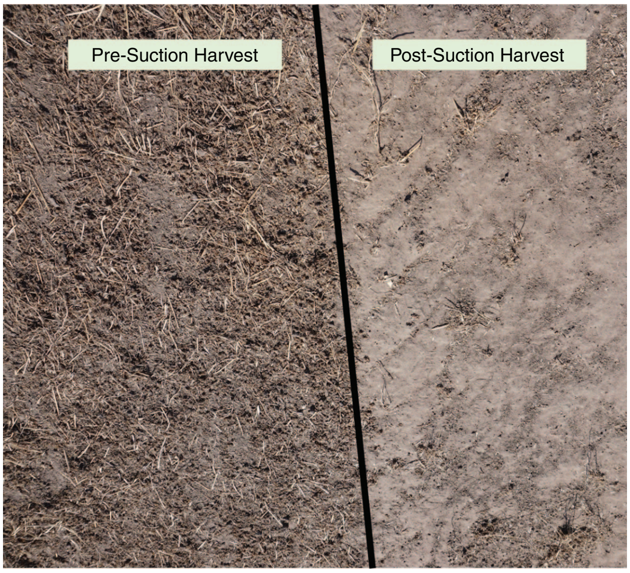

Fig. 5. Subterranean clover seed paddock surface pre-harvest after plant residue reduction, showing burrs brought to the surface (left) and immediately post-suction harvest (right). The majority of organic matter ground cover has been lost during suction harvest, leaving the paddock bare and prone to erosion.

n = 18) indicated they perform a post-harvest pass for erosion control. Three general erosion control methods are used.

(1) The most common is to roughen the soil surface to form clods and furrows. This is usually accomplished by harrowing, tilling or scarifying the soil. Air seeders with tynes or discs are also commonly used to cultivate the soil without sowing seed.
(2) Crops can be sown into the paddock to provide ground cover, particularly when there is access to irrigation. The act of seeding forms clods or furrows that reduce erosion. Moisture from irrigation can also temporarily reduce erosion.
(3) Ground coverings are also used in an attempt to reduce wind erosion. These can be straw, biosolids or any other material that will provide resistance to soil particle detachment and transport. For example, the Kybybolite/Koppamurra Landcare Group (P. Stuart, pers. comm.) experimented with the use of a straw covering and determined that spreading straw (cut to lengths 150–250 mm) at a rate of 500–750 kg/ha was an effective erosion mitigation technique.

Harvest equipment

The HB Clover Harvester remains the most common machine used in Australia for harvesting subterranean clover seed. One respondent also uses custom-made seed harvesting equipment to replace the HB. This consists of modifications to a rotary combine harvester to adapt it to harvest subterranean clover seed, although details of these modifications were not disclosed. In the case studies and workshops some references were made to other harvesting machines previously developed by farmers, however nearly all of these are not used today.

All surveyed current seed producers (100%, n = 16) own their own HBs, whereas one respondent additionally utilises contractor HBs. All survey respondents who answered on the quantity of HB ownership (100%, n = 12) owned multiple HBs (Fig. 6). Case study discussions indicated producers commonly kept at least one machine as a spare for break downs during harvest. Typical HB operating parameters are summarised in Table 3.

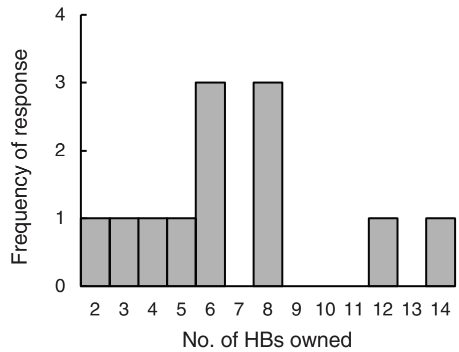

Fig. 6. The number of Horwood Bagshaw Clover Harvesters owned by each survey respondent (n = 12).

Table 3. Horwood Bagshaw Clover Harvester operating parameters
Summary of survey responses (n = 15) indicating how producers typically set up and operate their machines to harvest subterranean clover seed. The number of HB passes is a trade-off between seed capture, time and soil impact. Forward harvesting speed is affected by paddock seed yield, weather conditions and subterranean clover variety

	Median	Range
No. of total HB passes	2	1–3
No. of HBs in tandem behind single tractor	3	1–5
Forward harvesting speed (km/h)	2.5	1–4
Respondents utilising 1.22 m duct	89%	
Respondents utilising 2.14 m duct	11%	

Modifications to standard HB Clover Harvesters

HBs have been widely modified by farmers and local engineering workshops to improve on the original design and adapt to local conditions. All survey respondents (100%, n = 18) and case study producers have implemented modifications, the most common being the tandem drive (89%, n = 18), which allows multiple HBs to be towed and powered by a single tractor. Other modifications to increase performance were aimed at increasing seed storage (with enlarged bins or external trailers), or utilising modern components (fan and bearing replacements). Some producers have added brushes to their harvesters in an attempt to aid seed pick up, although the effectiveness of this is unknown and many brush modifications were later removed by producers. The majority of modifications have focussed on making HB operation and maintenance more convenient (adding inspection panels or fill sights, and relocating components for easier access). Three common modifications are depicted in Fig. 7.

Issues related to seed harvesting

The key issues identified by subterranean clover seed producers in the survey, case studies, and workshops were:

- soil erosion and degradation during pre-harvest preparation and suction harvesting,
- negative public perception of dust plumes during harvest and subsequent paddock erosion,
- HB Clover Harvester reliability and maintenance,
- the time and labour-intensive harvest process, with high fuel and labour costs,
- the impact of weather conditions on harvesting rate,
- the risk of harvest rain causing germination and reducing saleable yield,
- the high amount of foreign material picked up with the burr, which needs to be subsequently screened out, and
- soil and weed contamination biosecurity issues when selling interstate and internationally.

The survey respondents' perception of the single 'most significant' issue were (n = 11): efficiency and cost (36%), soil degradation and erosion (27%); harvester reliability and maintenance (27%); and weather impacts on harvest (9%).

Discussion

Harvest process

The harvest process for subterranean clover seed is time and labour-intensive, and has a significant negative impact on the soil. The process involves a high number of passes to prepare the paddock, work burr to the surface, harvest and thresh seeds, and finalise the paddock post-harvest. The median total (11) seed harvesting passes found in the survey is in line with the estimated 12 passes reported by Virgona (1996). Although harvest principles are similar across producers, the pre and post-harvest equipment and techniques employed can vary widely. Research is required to identify the most effective practices and develop techniques that address issues in the harvest process. However, the current harvest process is inherently linked to the suction harvest system, which is the root cause of many of these issues.

Pre-harvest preparation

Pre-harvest preparation is a vitally important aspect of the current suction harvesting process, but takes time and degrades the soil. New harvest technology or methods are needed to reduce the amount of preparation required and its impact on the soil.

Alternative preparation techniques are possible. Case study three provides an example of a novel procedure using only three passes following grazing – vertical blade power harrow, chain harrow, and suction harvest. The European style power harrow (Breviglieri Mekfarmer 220), set 2.5 cm deep, utilises blades rotating around a vertical axis to break up plant material and bring burr to the surface without inverting the soil layers. A chain link harrow further prepares the soil before a single suction pass with a HB harvests the subterranean clover seed. This producer operates on light, sandy soil where erosion is a key concern and forgoes post-harvest cultivation so not to disturb the soil further. It should be noted that seed yields here are relatively low (<500 kg/ha clean seed) compared with other districts with irrigation, where yields can exceed 1000 kg/ha. The power harrow approach may not work as effectively on higher yielding paddocks or heavier soil textures; however, it does provide a contrast to other more intensive harvesting systems. This case study was the only recorded instance of a power harrow being used in the industry and its potential for more widespread use should be investigated further.

Fig. 7. Examples of Horwood Bagshaw Clover Harvester modifications. (*a*) An external seed storage bin. (*b*) Broom ahead of pick-up duct. (*c*) Tandem drive kit allowing five HBs in a train behind a single tractor.

Post-harvest erosion control

Control of erosion is an important part of the harvest process. Although it does not affect harvesting of the seed, it helps to protect producers' soil and the sustainability of their operation. McIntosh *et al*. (2006) recommend maintaining greater than 50% groundcover or 50% large soil aggregates (clods) in order to reduce the risk of wind erosion on cultivated paddocks. Most seed producers attempt to implement this post-harvest, however the techniques used vary widely and there has been no formal evaluation of their efficacy. The erosion controls applied by producers depend on local soil conditions and resources available. For example, the equipment used to form clods varies depending on the equipment available to the producer from their other farm activities and there is no available best practice. In case study two, the use of a paper manufacturing waste covering is the result of close proximity to a paper mill, which allows easy access to this material. The range of methods used highlights the need for more research in this area. Further investigation should evaluate different erosion control methods and provide guidance on which treatments are most effective. However, this only attempts to mitigate the erosion issue and therefore new solutions should also seek to address the underlying cause of this problem: the harvest system and technology.

Suction harvesting

Suction harvesting is the quintessential feature of current subterranean clover seed production; however, it is almost completely reliant on early 1960s technology. This system is effective at harvesting seed, but only when burrs are brought to the surface. Bringing them to the surface requires soil disturbance and degradation. Suction harvesting then further impacts the soil and leaves the paddock bare and vulnerable to erosion. Refined methods of preparation and post-harvest erosion control may address some of these issues, but the root cause is the suction harvest system. Therefore, the most effective way to address the negative impacts of the current subterranean clover harvesting system on the soil will likely come from the development of alternative harvesting technology that avoids the use of suction.

Harvest equipment

The HB remains crucial in subterranean clover seed production. Nearly 60 years from its release, and three decades after the cessation of its manufacture, it is still used by practically all producers. While this is a credit to its design, it does underscore the need for innovation and new technology in the industry. This conclusion is particularly apparent when comparisons are made to the harvesting equipment for other crops, which have seen significant investment and innovation over the past decades to produce advances in production.

The HB harvest width (most commonly 1.22 m) is narrow for modern agricultural standards and represents a significant disadvantage. Grain combine harvesters developed from an average harvest width of 3 m in 1960 to 5 m in 1986 (Biondi *et al*. 1996), and today widths extend up to 13.8 m (Claas 2020). Peanut harvesting 'diggers' are manufactured in widths up to 8 m (KMC 2020). Suction peat harvesters utilise multiple pickup ducts for an effective width of 3.64 m (Premier Tech Chronos 2020). The HB's limited width is becoming increasingly salient when compared with advances in other equipment, however the major bottleneck in the machine is the material processing capacity. If this were increased, a larger pickup duct could be used, which would increase the harvest rate.

The harvest width and speed produce the harvest rate. The survey indicated HBs are typically driven at 2.5 km/h to harvest subterranean clover seed, which equates to an average harvest rate of 0.3 ha/h for the 1.22 m duct. This is an overestimate of the overall harvest efficiency, as turning, unloading and other operations add time when the machine is not harvesting. However, the overall efficiency can be increased by adding machines in tandem. Harvest rates for modern cereal combines are much higher than for the HB. For example, Busato *et al*. (2007) estimated a wheat combine (9 m width, 9.24 km/h average speed) in SA operates at 8.3 ha/h.

Although the rate at which the HB actually harvests subterranean clover seed is low, the overall seed harvesting process is even slower, given suction harvest passes are generally repeated and numerous other pre- and post-suction steps are required. With a median of 11 passes, the HB process results in a comparatively low overall harvest efficiency for subterranean clover seed. Most crop harvesting with a combine harvester can be completed in a single pass, including aerial-seeded pasture legumes such as balansa clover (*Trifolium michelianum* Savi), Persian clover (*T. resupinatum* L.), and arrowleaf clover (*T. vesiculosum* Savi) (Nichols *et al*. 2012). However, subterranean clover seed is buried, which presents unique harvesting challenges among the pasture legumes. There are other agricultural and horticultural crops harvested from beneath the soil surface; for example potatoes (*Solanum tuberosum* L.) are harvested from the ground in a single pass, but being significantly larger than subterranean clover burrs they are easier to separate from the soil. Peanuts (*Arachis hypogaea* L.) are a legume harvested from the soil in two passes – a digger cuts the tap root and lifts peanut clusters from the soil, leaving them in inverted windrows (peanuts facing up) to dry out on the surface, followed by a peanut combine harvester to pick up and thresh pods from the vines (Bader and Sumner 2009). Although none of these other crops are perfectly analogous to subterranean clover seed, they do provide examples of the advantages of harvesting with modern technology and methods. The comparisons also highlight the relatively low productivity of current subterranean clover harvesting equipment and the need for new technology. Harvest rates for agricultural equipment are shown in Table 4, which all significantly exceed that of the HB.

Alternatives to the HB

Although the HB is ubiquitous in the industry, there have been attempts at utilising alternative harvesting methods. Some seed producers have attempted to harvest subterranean clover burrs with conventional or modified cereal combines, where the plant is typically windrowed before being picked up and threshed by the machine. This appears best suited to varieties of subspecies *brachycalycinum*, which has limited

Table 4. Harvest rates of various agricultural equipment

Equipment	Harvest rate[A] (ha/h)	Source
Wheat combine harvester	8.3	Busato *et al*. (2007)
Peanut digger	5.2	Bader and Sumner (2009)
Suction peat harvester	2.7	Premier Tech Chronos (2020)
Potato harvester	1.0	Olukunle (2010)
Single HB subterranean clover seed harvester	0.3	Survey (this study)

[A]Harvest rate estimated from average harvest speed and width, but will vary by conditions and equipment.

burr burial compared with ssp. *subterraneum* and ssp. *yanninicum* (Nichols *et al*. 2012). Utilising cereal combine harvesters has achieved varying levels of success; however, the general consensus of seed producers is that the practice leaves too much unharvested seed in the paddock, requiring deployment of a HB harvester to collect the remaining burr. Furthermore, the cereal harvester's large threshing drum, sieves and threshing bars are designed for coarse grains and are not well suited to the smaller subterranean clover seeds, which can cause seed loss through the machine. Another significant issue is that large amounts of soil are ingested while harvesting material from the ground, which increases the rate of wear in the combine. In order to reduce soil ingress into the combine, an intermediary step or process is needed to remove soil from the plant matter and burrs. Being able to harvest subterranean clover seed with a combine would be extremely advantageous for the industry, but it appears significantly more research is required to design systems to make this viable, particularly for all three subspecies of subterranean clover.

The other harvest equipment mentioned in the survey, case studies, and workshops included alternate custom-built vacuum style harvesters or systems using brushes to collect burrs, but only minimal information was provided. These harvesters were developed and built on-farm and were not commercialised, and as such there is limited information available on their design and use. Future research should explore and document the alternatives to the HB that have been created, in order to understand what has already been attempted, the reasons for their lack of success and to aid the design of new technology.

HB modifications

There have been various and extensive modifications made to the HB over the decades (Moss *et al*. in press). Despite some of these modifications (most notably the tandem drive) providing significant improvements over the original design, harvesting issues remain. Many modifications have been implemented, but there is not a clear understanding of their effectiveness. Benefits from modifications that aid maintenance and convenience are clearer, but advantages in harvest efficiency are more opaque. Further work should aim to analyse and test modifications to determine their efficacy and provide guidance to seed producers on which modifications might be valuable for their operation.

Although modifications can be beneficial, after 60 years of adapting the HB, new modifications may have reached a point of diminishing returns. Furthermore, HB modifications have primarily produced only incremental improvements e.g. increasing harvest rate by adding machines in tandem or reducing stopping frequency by expanding seed bin sizes. These efforts have focussed on improvements, rather than innovation. Moss *et al*. (2021) discuss several HB modifications and conclude that while there is potential for further improvement, there is a ceiling imposed by reliance on the underlying technology. This finding supports the notion that new technology is needed in the industry. Since many problems stem from the current harvest equipment and procedures, future modifications are constrained by the original design and appear unable to substantially address the underlying issues affecting subterranean clover seed harvesting.

Industry issues

This study has reinforced that there are issues currently affecting the subterranean clover seed industry, principally the slow, inefficient, and labour-intensive harvest process that negatively impacts the soil. Problems specifically related to operation of the HB were also highlighted, primarily: reliability and serviceability issues, material processing efficiency, seed harvest losses, soil contamination in seed sample and excessive wear from sand. The root cause of these issues appears to be the current harvest technology. Avery *et al*. (2001), Loi *et al*. (2005) and Nichols *et al*. (2013) have noted the decline in the number of subterranean clover seed producers, a decline that has the potential to continue if new harvest machinery is not implemented to address these issues.

The potential for erosion during the harvesting process was expressed as a key issue in the survey, case studies, and workshops. Degradation of soil structure from mechanical action and removal of plant cover increases the risk of erosion, which can result in the removal of soil nutrients (Pimentel 2006). In addition to soil damage in their paddocks, producers also expressed concern about negative public perception. The extremely dusty nature of suction harvesting is highly visible to the public and can affect air quality in the surrounding area. Bare paddocks and post-harvest erosion impact the industry's reputation amid increased awareness of 'sustainable agriculture' and 'conservation agriculture' systems, which incorporate soil cover and nil or minimum mechanical soil disturbance for soil conservation (Pretty *et al*. 2018; Kassam *et al*. 2019). Harvesting practices are also at odds with the widespread Australian adoption of no-till stubble retention systems in cropping (Llewellyn *et al*. 2012; Mehra *et al*. 2018). These negative perceptions threaten seed producers' social licence to operate. Harvest-related soil degradation is inherently linked to the HB technology and is a further reason new harvest equipment and methods are required.

There are also issues with reliability and maintenance of the HB. The newest machines in use are approaching 30 years old and some are nearly 60 years old. The age of the machinery, combined with the lack of commercially-available parts, means the HBs are prone to breakdown. Bespoke parts are then required to maintain the equipment. The harvesters themselves can be difficult to obtain, with producers reticent to sell machines even if they are no longer used, which acts as a significant barrier to the entry for new producers. HBs are only getting older and their numbers fewer, driving the need for new equipment in the industry.

The high labour rates, fuel, and equipment use time of the current HB harvest systems represent a significant cost to seed producers. The low harvest efficiency, from old machinery and many passes, results in a high harvest cost for subterranean clover seed and unless the price of seed is sufficiently high, these activities are no longer profitable compared with performing other farming operations. It is not solely the efficiency of modern equipment with which the HB must compete, but also the increases in convenience and technology. Olukunle (2010) notes the most important improvements in modern combine harvesters have been in comfort and ergonomics, making equipment easier, less tiring and safer for the human operator. Technology in modern equipment also allows farmers an ever-growing understanding of their operation, which is increasingly important as data becomes a valuable farm commodity (Kamilaris *et al.* 2017). These advances in other areas make subterranean clover seed harvesting comparatively less attractive, disincentivising new producers from entering the industry and highlighting the need for advances in subterranean clover seed technology.

The impact of weather conditions is another important factor for harvesting operations. The HB's slow harvest speed can be further reduced by adverse weather. Harvesting efficiency is negatively affected by low temperature and high humidity. Producers reported that the HB functions best in hot, dry conditions, and it is more difficult to thresh the plant material in high humidity. Anecdotes from seed producers relate that areas that can be harvested in a week during hot weather can take over a month in cooler weather. Longer harvest times increase the financial risk for the seed producer, as significant rainfall events can cause seed germination, impact seed viability and reduce the amount of saleable seed. Although the weather cannot be controlled, harvest equipment with greater flexibility could help mitigate this issue. These harvesters could have the ability to collect burr in any conditions to be processed later, or have internal climate control to create the correct conditions for threshing. The feasibility and practicality of this adaptable machinery is unclear, however the current weather dependence of harvest operations is directly linked to the HB's design and could be improved with new technology.

Another design issue associated with the HB is the high amount of soil and plant material picked up with burrs, requiring harvested seed to be transported to a cleaning facility to remove material before the seed can be sold. Didar (2003) found that Paraggio barrel medic (*Medicago truncatula* Gaertn.) pods and some soil particles were aerodynamically similar and could not be distinguished at pickup by the HB, which is likely also true for similarly-sized subterranean clover burrs. This contamination, particularly that of soil, incurs extra transport costs for seed producers and creates biosecurity difficulties for seed companies selling seed interstate and internationally. Interaction with soil for buried burrs is inevitable and soil adheres to the burrs themselves, however there are negative characteristics associated with suction harvesting that compound the issue. Inevitably, the HB system will ingest soil along with burr, which is a fundamental challenge of the suction harvest system.

Compatible technology from other industries

Here we have highlighted the need to investigate new technology for subterranean clover seed harvesting. However, to provide tangible benefits to the industry this equipment would need to be economically developed, manufactured and marketed to seed producers. As noted by Hassall and Associates (2001), the small size of the pasture seed industry presents challenges in profitably producing new equipment. Therefore, new subterranean clover seed harvesting machinery should aim to utilise technology from other industries.

Modern suction harvesters are produced for peat and turf industries (e.g. Premier Tech Chronos peat harvesters and Trilo turf equipment). These harvesters could potentially be adapted to effectively pick up burrs, however this material would still require subsequent threshing and processing. The paddock would still need to be prepared to bring burrs to the surface and issues of soil erosion and degradation remain. Therefore, alternatives to suction systems need to be investigated.

Industries that harvest products from below the ground, for example, carrots, potatoes, and peanuts, are likely to be a better avenue for exploration. Of these, peanuts are the most similar to subterranean clover seed, both being legumes harvested from beneath the soil. Peanut harvesting has developed to efficiently extract pods from the ground with no preparation passes, minimal product loss or soil impact, and both stages of the harvest process (digger and thresher) have an emphasis on reducing soil retention and ingestion into equipment (Bader and Sumner 2009). This peanut system strongly aligns with the objectives of subterranean clover seed harvesting. Peanut harvesting technology therefore has the potential to be adapted for subterranean clover seed harvesting and, with its existing commercial supply chain, it could provide modern technology to subterranean clover seed producers. However, different seed production agronomy, harvest timing and soil types may need to be investigated for these alternative systems to be most successful in subterranean clover seed production.

Aerial-seeding annual pasture legumes as alternatives to subterranean clover

Before 1990, the annual pasture legume options in southern Australia were largely confined to subterranean clover and annual medics. However, several sustainability and economic challenges to farming systems led to a targeted expansion in the range of pasture legume options in order to provide producers with new cultivars and species with traits to meet the needs of current and prospective farming systems. For instance, over the past three decades, cultivars of several aerial-seeding annual pasture legume species adapted to similar soil types to subterranean clover have been released in Australia, including French serradella (*Ornithopus sativus* Brot.), biserrula (*Biserrula pelecinus* L.), gland clover (*Trifolium glanduliferum* Boiss.), bladder clover (*T. spumosum* L.), balansa clover, arrowleaf clover, Persian clover, crimson clover (*T. incarnatum* L.), purple clover (*T. purpureum* Loisel.), and Eastern star clover (*T. dasyurum* C. Presl.) (Loi *et al*. 2005; Nichols *et al*. 2007, 2012). Two key drivers for this diversification were the shift away from traditional regenerating ley systems, which created a need for lower cost seed for use when frequently re-sowing pastures following cropping phases, and environmental concerns about the soil erosion caused by the suction harvest of subterranean clover seeds (several other perceived weaknesses of subterranean clover may also have been drivers) (Ewing 1999; Loi *et al*. 2005; Nichols *et al*. 2007, 2012). A major advantage of the aerial-seeding annual pasture legumes is they are suitable for seed harvest with conventional crop harvesting machinery, resulting in lower-cost seed. However, there are many regional and ecological differences across southern Australia and the management of aerial-seeding pasture legume species to maximise their productivity and persistence often needs further work as their cultivar development and agronomy has a very short history compared with that of subterranean clover. For instance, Boschma *et al*. (2019) found that many current serradella cultivars have unstable flowering dates and hence when germinating on an early break in eastern Australia may flower too early, during severe frost periods, and thus set insufficient seed for adequate pasture regeneration the following season. At this stage, these alternative species can be regarded as complementary to subterranean clover, often for use in specific situations, rather than as broad-scale replacements for the species. Thus, in spite of the release of many new species and cultivars, subterranean clover remains popular with Australian producers for its grazing tolerance and general ease of management, as reflected in it comprising 52% of all annual legume certified seed tonnage in 2018/19 (Australian Seeds Authority 2020*b*). This ongoing demand for subterranean clover seed justifies efforts to develop improved seed harvesting technology.

Limitations of the study

The response size of the survey is small and is a limitation of this study. The distribution method and unknown industry size mean that a survey response rate cannot be calculated. However, the authors believe the 18 responses to be representative of the seed production industry, given the low estimated number of seed producers. Survey results are consistent with findings from case studies and workshops, which are discussed together to draw insights into seed harvesting practices. The survey size of 18 is an improvement from the 11 subterranean clover seed producer respondents in the Hassall and Associates (2001) survey.

Conclusions and future work

This study concludes that current subterranean clover seed harvesting practices are time, labour and resource intensive contributing to soil degradation and erosion. It also highlights several reliability, maintenance and efficiency issues associated with the aging HB. The results of the survey, workshops and case studies support our hypothesis that the primary cause of these issues is the HB Clover Harvester technology and its associated harvesting procedures.

Results from this study provide insights into how producers use HBs, the modifications they have made and the problems they still face. These insights will support future development of solutions relevant to seed producers and capable of addressing issues in the industry. Aerial-seeding annual pasture legume species are able to be collected with conventional crop harvesting equipment, but limitations of these species and the continued demand for subterranean clover justifies the need for further research to improve subterranean clover seed harvesting. Future work should focus on the following factors.

(1) Evaluation of the different harvest preparation techniques.
(2) Evaluation of the common post-harvest erosion control treatments.
(3) Evaluation of the effectiveness of existing HB modifications.
(4) Development of new HB modifications.
(5) Documentation and evaluation of lesser-known subterranean clover seed harvesters.
(6) Development of new seed harvesting equipment.

Recommendations 1–4 could provide benefits to the seed industry, however they do not address the issues' root cause: the suction harvest system itself. Therefore future subterranean clover seed production research should primarily focus on investigating innovative new solutions to harvest seed in order to replace the Horwood Bagshaw Clover Harvester.

Conflicts of interest

The authors have no conflicts of interest to declare.

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