Economic implications of the loss of glyphosate and paraquat on central wheatbelt broadacre farms in WA

Alison Elizabeth Walsh

Professor Ross Kingwell

Associate Professor James Fogarty

This thesis is submitted to fulfil the requirements for Master of Science (enrolled
Program, Agricultural Economics) by way of Thesis & Coursework
Faculty of Science
The University of Western Australia.
(May 2021)

Table of Contents

Acknowledgements

Thank you, Ross, for giving me the opportunity to work on this research project. I am grateful for all I have learnt and getting to fall down many research rabbit holes. Researching such an interesting topic has brought me much excitement and joy.

James Fogarty thank you for your always helpful guidance.

Thank you, John Young, for helping me with the all the intricacies of MIDAS.

Thank you Chus for being the best friend and supporting to me always. Mum, thank you for always being ready to give up your time to read my work, never once complaining. James, thank you for always being supportive and making me delicious dinners when I am stressed.

1. Abstract

Glyphosate and paraquat are effective, affordable non-selective herbicides widely used in Australian agriculture. However, for reasons described in this study, their use is under threat and a ban on their use is a possibility. Using the bioeconomic farm model, MIDAS to represent central wheatbelt farms of Western Australia, this study describes the farm business and farming system changes resulting from a ban on use of glyphosate and paraquat. The costs imposed through loss of these herbicides are estimated to cause increased costs of crop production and large declines in farm profit, if the herbicide ban does not similarly apply to other major grain exporters. Farming systems shift towards sheep production and away from cropping, increasing farms' greenhouse gas emissions. Farm businesses that are more crop dominant experience the greatest declines in profit with potential declines from $103,000 of up to $240,000. Despite several tactics and investments that farmers might employ to combat the loss of these herbicides, none prevents a reduction in farm profit. For the average farm, a $170,000 decline in farm profit is possible, although lesser declines are more likely. The likelihood of declines in profit will speed the invention and development of cost-effective alternative means of weed control.

2. Introduction

Glyphosate and paraquat are commonly applied herbicides integral to Australian agriculture. Glyphosate first became available in Australia in 1974. By 1997, 7,327 t of glyphosate was being used in Australian agriculture and by 2003 the use of glyphosate had increased almost fourfold to 26,334 t (DAWE 2007). In 2019, Bayer Crop Science stated: "around $400 million of glyphosate-based products are sold in the Australian market each year—the largest selling agricultural chemical product on the Australian market." (Rural and Regional Affairs and Transport Committee 2019, p. 58). Farmers' most recent use of glyphosate was reported by Harries *et al.* (2020). They surveyed 184 paddocks in Western Australia (WA) over six years and found glyphosate was frequently applied, about once per year, per paddock, at a rate of 500-750 grams per hectare.

In Australia, glyphosate use is far greater than paraquat use. Currently, it is widely used to complement glyphosate in controlling weeds prior to crop sowing in what is known as a double-knock operation. However, as paraquat is widely acknowledged to be far more toxic than glyphosate, its use is more prescribed. Paraquat is already banned in more than

50 countries due to its high toxicity and use in suicides (Kim and Kim 2020). For example, paraquat has been banned in the European Union since 2007 and in the USA paraquat is limited to use only by licensed applicators. In Australia, glyphosate use is far greater than paraquat use. Sales of glyphosate are six times larger than sales of paraquat (DAE 2013).

Subsequent sections of this thesis focus on how the ongoing popular use of glyphosate is under challenge, even to the point where a ban on use of glyphosate is being discussed. For example, a 2019 senate committee review in Australia heard evidence about challenges facing continued use of glyphosate, with the review concluding that "neither the government nor industry has contemplated a loss of access to glyphosate or the impact in Australia of a ban on glyphosate overseas." (Rural and Regional Affairs and Transport Committee 2019, p. 88).

Accordingly, this thesis's contribution to this knowledge gap is to examine the farming system and economic consequences of a ban on glyphosate and paraquat for central wheatbelt farms in WA. Prior to conducting this impact analysis, an overview of recent changes to the WA broadacre farming system is presented, including a description of the role that glyphosate and paraquat play in this farming system, and constraints on the use of glyphosate and paraquat.

2.1 Broadacre farming in Australia and the role of glyphosate and paraquat

2.1.1 Development of Conservation Agriculture in Australia

Prior to the 1970s weeds on broadacre farms were managed primarily through tillage, and to a lesser extent by burning crop residues (Walsh *et al.* 2020a). The advent of the non-selective herbicides, glyphosate and paraquat, for pre-seeding weed control, as well as selective herbicides for in crop weed control enabled the transition of many Australian farms into conservation agriculture (CA) (Walsh *et al.* 2020a). CA is characterised by minimal or no-tillage that reduces soil exposure to wind erosion. These benefits of reduced soil erosion allowed improvements in farm profits in Australia (Pannell *et al.* 2016).

The expiration of patents for paraquat and especially glyphosate, and a subsequent drop in the their prices played a significant role in doubling the adoption rate of no-tillage practices during 1990 to 2003 (D'Emden *et al.* 2006). CA improved soil structure and soil water retention (Farooq and Siddique 2015). Yields and yield stability increased following adoption of CA (Beckie *et al.* 2020). The benefits of CA, however, went beyond improved soil quality and yields. CA resulted in more efficient use of fuel, time and labour (Kirkegaard *et al.* 2014).

Changes in crop establishment techniques also occurred in response to a long-term decline in growing season rainfall (Turner 2011; CSIRO and BOM 2018). The reduced availability of dryland agriculture's most important input, water, made improving water use efficiency a priority when selecting agricultural practices. Changes in agronomic practices, such as no-tillage and reducing weeds, improved water use efficiency (Turner 2011).

From 1989 to 1998, on average, the relative return of cropping to sheep increased (Chauhan *et al.* 2006). Most broadacre farmers in the 1990s and 2000s accordingly altered their enterprise mix to favour cropping (Doole *et al.* 2009). Labour scarcity also emerged as a major limit to agricultural production, as found in a 2007 survey conducted by Rabobank (Rabobank 2007). In response, farm owners opted to work more hours themselves and shifted away from labour-intensive enterprises, such as intensive sheep production, further explaining land use change during the 1990s and 2000s. In cropping systems, glyphosate simplified weed control and reduced the labour required to manage weeds via tillage.

2.1.2 Dry seeding

To adapt to declining in-season rainfall and to accommodate larger cropping programs, Australian farmers also moved to dry seeding, allowing crops to use water more efficiently (Kirkegaard and Hunt 2010). Explaining further; dry seeding is where the seed is sown into dry soil before the break of season (Fletcher *et al.* 2020). Weed seeds in the soil germinate and grow with the crop, requiring control through the use of selective herbicides instead of non-selective such as glyphosate or paraquat. Dry seeding allows seeding to take place over a longer period, reducing capital expenditure on high work rates and large seeding machinery. Labour pressure over seeding is also lessened by dry seeding (Fletcher *et al.* 2016). However, if weed density in a paddock prior to seeding is high the use of glyphosate or paraquat may be required. This necessitates delaying seeding which incurs yield penalties, as the subsequent later sowing occurs when soils are cooler causing slower seedling emergence and plant growth; and the subsequent use of in-season rainfall by the crop is also less effective (Fletcher *et al*. 2020). Delayed seeding also reduces the competitiveness of a crop, potentially resulting in weed species like annual ryegrass having greater seed production (Gill and Fleet 2020).

2.1.3 Genetically modified crops

In most Australian cropping systems, glyphosate is applied prior to seeding and during fallow. However, the introduction of glyphosate tolerant (GT) crops allowed glyphosate to also be used within crop, as a broad-spectrum non-selective post-emergent herbicide. An initial impediment to use of glyphosate in Australian agriculture was the strong opposition to genetically modified crops. Despite Roundup Ready® canola (i.e. GT canola) receiving its licence for commercial cultivation in Australia in 2003 (OGTR 2003), the state governments in all canola-producing states placed moratoriums on the planting of GT canola. Subsequently, after several years, all these bans were lifted, although the South Australian moratorium lasted until early 2020. In 2017, 21% of the national canola crop was GT canola (OGTR 2020) which boosted the use of glyphosate.

If glyphosate could no longer be used, GT crops could no longer be grown in Australia and Australia’s main GT crop, GT canola, would be replaced by another form of canola, such as Triazine or Imidazoline tolerant canola, or another crop or pasture option.

Herbicide tolerant crops other than GT crops, can lessen farmers’ reliance on glyphosate. For example, triazine and imidazoline tolerant canola, both derived through conventional breeding methods, facilitate control of broadleaf weeds (Stanton *et al*. 2010). If farmers lose access to glyphosate and therefore have little incentive to plant GT canola, then triazine and imidazoline tolerant canola would be more frequently grown. However, an additional cost would be a greater likelihood of weeds forming resistance to triazine and imidazoline. Although herbicide tolerant varieties initially increase farmers’ weed control options, their continued use increases selection pressure on weed populations causing an increased emergence of herbicide resistant weed populations (Preston *et al*. 1999; Powles *et al.* 1998; Burnet *et al.* 1991).

2.2 Constraints on the use of glyphosate and paraquat

2.2.1 The development of herbicide resistant weeds

Weeds lessen crop yields and reduce agricultural productivity (Oerke 2006). Annually, weed management in Australia costs $2.5 billion and yield losses associated with weeds cost $745 million (Llewellyn *et al.* 2016). Weed management in Australia has greatly depended on access to glyphosate and paraquat over the last three decades. However, the ubiquitous use of glyphosate, in particular, has become tempered by the emergence of certain weed populations resistant to glyphosate or paraquat that lessen their efficacy and limit their widespread use.

In 1996 the first glyphosate resistant weed, annual ryegrass, was documented in Australia (Pratley *et al.* 1996; Powles *et al.* 1998). Currently in Australia there are 17 species with recorded instances of glyphosate resistance. Sole or main reliance on glyphosate, combined with its repetitious use, increase the selection pressure for weeds with biological characteristics that tolerate glyphosate (Werth *et al.* 2013). Weeds which survive herbicide applications have higher rates of alleles resistant to that herbicide (Jasieniuk *et al*. 1996). The persistent use of the same herbicide or herbicides with the same mode of action imposes intense selection pressure on weed populations, leading to emergence of weeds resistant to that herbicide (Jasieniuk *et al*. 1996). The mode of action of a herbicide, how that herbicide kills the plant, determines which herbicide group the herbicide belongs. Glyphosate is a group M herbicide and paraquat is in group L. Continued emergence of weed populations displaying resistance to glyphosate limits greater use of glyphosate in Australia's cropping systems.

Through Integrated Weed Management (IWM), where growers use several weed control methods, the emergence of glyphosate resistant weed populations is delayed (Pannell and Gill 1994; Pannell *et al*. 2004). Herbicide resistance, however, is not isolated to glyphosate. Currently in Australia 49 weed species display herbicide resistance (Weed Science Organisation 2020). Reducing the selection pressure for resistance is the primary method for managing the evolution of herbicide resistant weeds (Beckie 2006). IWM is now widely applied throughout Australia. A survey by Llewellyn *et al.* (2004) of 132 grain growers in WA found all growers applied IWM, the mean number of practices used was 7.7. Hence, farmers' weed management is already combating the likelihood of emergence and spread of GT weeds.

While herbicides continue to be applied, herbicide resistant weed populations will continue to evolve. Using non-herbicide weed control methods such as harvest weed seed control (Jacobs and Kingwell 2016), tillage based site-specific weed control and rotations to manage weeds, rather than solely relying on herbicides, lessen the selection pressure for herbicide tolerant weeds (Pannell *et al.* 2004). These technologies provide effective non-chemical alternatives and allow for dry seeding (Walsh *et al.* 2013).

2.2.2 Glyphosate's lessening social licence

A number of epidemiological studies have found frequent use and exposure to glyphosate is linked to an increased risk of non-Hodgkin's lymphoma (Myers *et al.* 2016; Zhang *et al.* 2019) or a sub-type of non-Hodgkin's lymphoma, diffuse large B-cell lymphoma (Leon *et al.* 2019). Accordingly, due to the frequent and extensive use of glyphosate, concerns have arisen about the safety of its use. Glyphosate, and its breakdown product aminoethyl-phosphonic acid, (AMPA) have been found to persist in soil and water (Van Bruggen *et al.* 2018), as well as in the air and rain during summer in North America (Battaglin *et al.* 2014). This raises concerns of its persistence in the environment (Kanissery *et al.* 2019). However, when these studies are compared against other experimental results in the literature that report glyphosate's behaviour within soil and water, and its persistence, no scientific consensus emerges. Often results vary and are contradictory (Padilla and Selim 2020).

The contamination hazard of glyphosate and AMPA was modelled and mapped by Maggi *et al.* (2020) (Figure 1). Persistence and biodegradation recalcitrance of these two compounds were strong determinants of hazard hotspots, defined as areas with mid-high to high level contamination hazard. While Australia does not have any contamination hotspots, all mainland states do have some low-level contamination hazard. Globally, despite the ubiquitous use of glyphosate, there are relatively few hotspots, although low-level contamination is widespread (Figure 1) (Maggi *et al.* 2020).

A key report on the health risk of glyphosate was released in 2015 by the International Agency for Research on Cancer (IARC), part of the World Health Organisation (WHO). The IARC (2015) classified glyphosate as, "probably carcinogenic to humans". Since the release of the WHO's classification, public concern about the safety of glyphosate has grown, despite many countries' chemical regulators (e.g. European Food Safety Authority, the European Chemicals Agency, the USA's Environmental Protection Agency, Canada's Pest Management Regulatory Agency, and the Australian Pesticides and Veterinary Medicine Authority) deeming the herbicide safe to use when used in accordance to label instructions (e.g. USEPA 2016; APVMA 2017; EFSA 2019; ECA 2019). Nonetheless, legal cases have been brought against Monsanto, now owned by Bayer, for damages relating to glyphosate causing cancer.

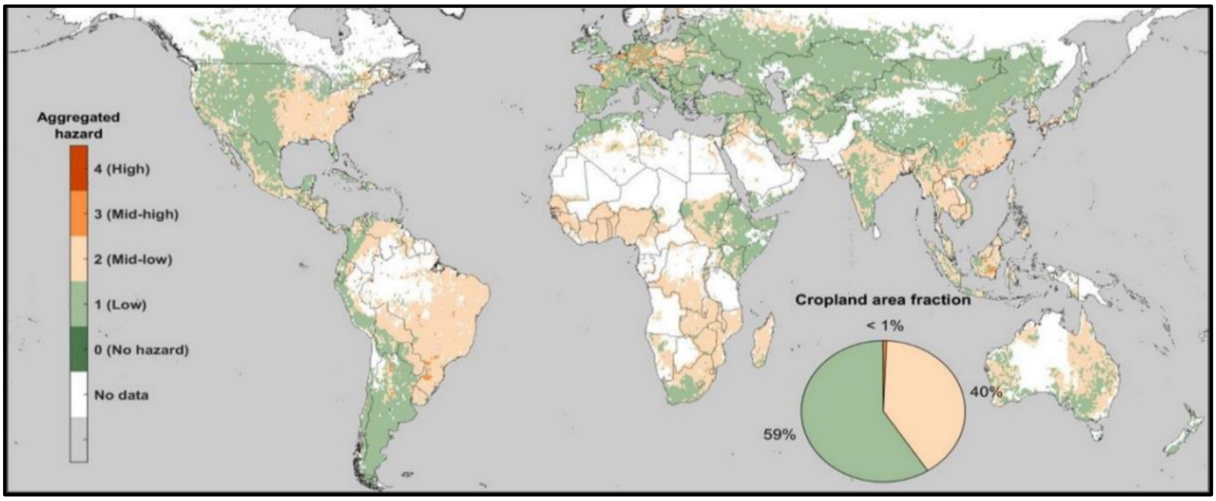

Figure 1. Geographic distribution of glyphosate-related contamination hazard resulting from biodegradation recalcitrance, residue accumulation in the top soil, leaching below the root zone, and persistence. (Source: Maggi *et al.* 2020).

In the USA since the IARC classification in 2015 over 125,000 lawsuits were brought against Bayer by those claiming glyphosate was the cause of their cancers. In Australia the first legal case arose in 2019 and there is currently a class action lawsuit before the federal courts against Monsanto in Australia for misleading its customers by suggesting glyphosate posed no health risks when used in accordance with label instructions.

In the USA in June 2020, Bayer announced it would allocate up to USD10.9 billion to settle approximately 95,000 lawsuits brought by individuals who claimed their non-Hodgkin's lymphoma was due to exposure to glyphosate (ABC 2020). Bayer has said no agreement had yet been reached for about 25,000 remaining claims. In June 2020, Bayer also filed a class action in San Francisco to settle all future claims of individuals who use Roundup (i.e. glyphosate) but have not yet manifested non-Hodgkin's lymphoma. Bayer also announced the creation of a science panel which, over the next four years, would study Roundup and render a decision on whether the herbicide causes non-Hodgkin's lymphoma.

A proscribed social licence governing the use of glyphosate is emerging due to the combined influences of successful legal cases, the IARC classification and the accompanying furore of adverse media attention. A ban on use of glyphosate has been called for by various interest groups in several countries, and an actual ban applies in an increasing number of countries. Glyphosate use in public spaces has now been banned in countries such as the Netherlands, France and Italy (Tosun *et al*. 2019). The six Middle East gulf countries issued glyphosate bans from 2019. Luxembourg banned use of glyphosate from December 31, 2020 and the French government announced the cessation of use of glyphosate use by 2021. In Australia, many local councils have banned or are phasing out use of glyphosate. In 2020, Kellogg’s announced, in its supply chains, it will phase out by 2025 wheat and oats treated with glyphosate as a drying agent.

The increased risks of litigation surrounding use of glyphosate, when combined with social media pressure on governments to restrict the use of glyphosate could firstly result in greater regulatory control over the use of glyphosate in agriculture. Secondly, countries that receive Australian agricultural exports may introduce regulations that force Australian farmers exporting products to those countries to abandon or lessen their use of glyphosate. Currently, in key grain export markets for Australian grain, few maximum residue levels (MRLs) for glyphosate are less than Australia’s. It is foreseeable that some countries could introduce MRLs for glyphosate so low that any grain exported to that country will need to come from production systems in which no glyphosate is used. Unless grain traders and shippers are assured that the grain they export comes solely from production systems not dependent on glyphosate, they will be reticent to purchase and trade that grain due to the commercial risk of grain cargo rejection. In such a situation, for example, the application of glyphosate prior to harvest as a drying agent, also referred to as crop desiccation, would be banned. This is where glyphosate is applied to the crop pre-harvest to even ripening and control summer weeds under the canopy (Cameron and Storrie 2014).

The health-related lawsuits brought against Bayer are in one way unexpected. When glyphosate first became available, a driver of its adoption was its lower toxicity when compared to other herbicide alternatives, such as paraquat. This is still true (Duke 2018).

Kniss (2017) examined the long-term trends in the intensity and relative toxicity of herbicide use in the USA and found glyphosate less acutely toxic than 94% of the 159 herbicides in use over the 25-year survey period.

Paraquat, a broad-spectrum herbicide, is a close alternative to glyphosate, yet paraquat is much more toxic. The LD_{50} metric is calculated as the lethal dose required to kill 50% of the test cohort. The LD_{50} for paraquat is 150 mg/kg and for glyphosate it is 4,230 mg/kg (WHO 2010). That is, paraquat is 28 times more toxic than glyphosate. Were glyphosate no longer available, paraquat would be a likely substitute. The perverse situation would arise where, to lessen use of glyphosate, an even more toxic herbicide would increasingly be used. When this behaviour becomes known, it is foreseeable that social and media pressure will arise to prevent the use of paraquat in agriculture, due to its greater toxicity and alleged links to increased likelihood of proneness to Parkinson’s disease (Tangamornsuksan *et al*., 2019). Paraquat has already been banned in more than 50 countries due to its high toxicity and use in suicides (Kim and Kim 2020).

Developing herbicides that offer a different mode of action to glyphosate or paraquat would reduce farmers’ dependence on these herbicides. However, such a discovery is remarkably rare as evidenced by this comment of Bayer Crop Science: ‘Thirty years ago, an average of one in every 10,000 compounds that were tested could be developed for commercial release. Now that rate is only one in every 50,000.’ (Rural and Regional Affairs and Transport Committee 2019, p. 62). Duke (2012) observed that in the 20 years prior to his review, no major commercial herbicide had been introduced containing an active ingredient with a new mode of action.

2.3 Changes to Australia’s cropping farm systems under the loss of glyphosate and paraquat

As demonstrated by the quantity and frequency of their use, Australian agriculture is reliant on glyphosate and paraquat for weed control and to-date there has been little attention devoted to examining the implications of the loss of access to these herbicides. In the specific case of agriculture in WA there has been no examination of the economic consequences for WA broadacre farms of loss of access to these herbicides.

Discussions with farmers, agronomists and weed scientists reveal some potentially serious consequences could flow from farmers no longer having access to these herbicides. These consequences are discussed in the following paragraphs.

Summer weeds utilise plant available water and nitrogen, causing yield implications for the subsequent crop (Haskins and Mcmaster 2012). The presence of summer weeds also allows crop diseases such as rust to be carried temporally through the soil, providing a ‘green bridge’ (Cameron and Storrie 2014). At the break of season, without effective weed management, mechanical sowing can be impaired due to blockages by weeds, causing delays in sowing (Cameron and Storrie 2014). A ‘double knock’, whereby a single germination of weeds is applied with two weed control measures with different modes of action, is often the only weed control tactic that controls summer weeds adequately. Glyphosate and paraquat are by far the most common double knock down combination (Harries *et al.* 2020). Without glyphosate and paraquat, effective summer weed control will likely become difficult.

At the farm level, the loss of use of glyphosate and paraquat are likely to increase the unit cost of grain production, as these herbicides are effective and cheap. A ban on their use would in the short term reduce farmers’ profits from crop production. The loss of access to glyphosate would likely have a cascade of effects. GT canola would disappear from cropping systems and there would be greater investments in other forms of weed control such as harvest weed seed control (HWSC) technology. The practice of HWSC, through modifications to harvesting machinery, collects weed seeds as they pass through the harvester, preventing those weed seeds from entering the soil seed bank, reducing weed incidences in following seasons (GRDC 2018).

The modelling analysis which follows in Section 4 outlines the farming system and economic impacts of loss of glyphosate and paraquat for representative farms in the central wheatbelt of WA.

3. Hypotheses

The farm modelling described in Section 4 is used to test two hypotheses:

1. Loss of glyphosate and paraquat affects the whole farming system.
2. Loss of glyphosate and paraquat reduces farm profit.

4. Methodology

4.1 MIDAS

To test these hypotheses the economic and farming system consequences of loss of access to glyphosate and paraquat was modelled via use of the bioeconomic model, MIDAS. MIDAS is a whole farm, steady state, linear programming optimisation model which maximises net profits whilst integrating biological, physical and financial features of the farming system (Kingwell and Pannell 1987). The Central Wheatbelt version of MIDAS was used, the study area is shown in Figure 2. This version of MIDAS is a representative farm of 3,750 hectares with annual rainfall of 350-400 mm and is characterised by eight land management units (LMUs) that represent the soil heterogeneity of farms in the region.

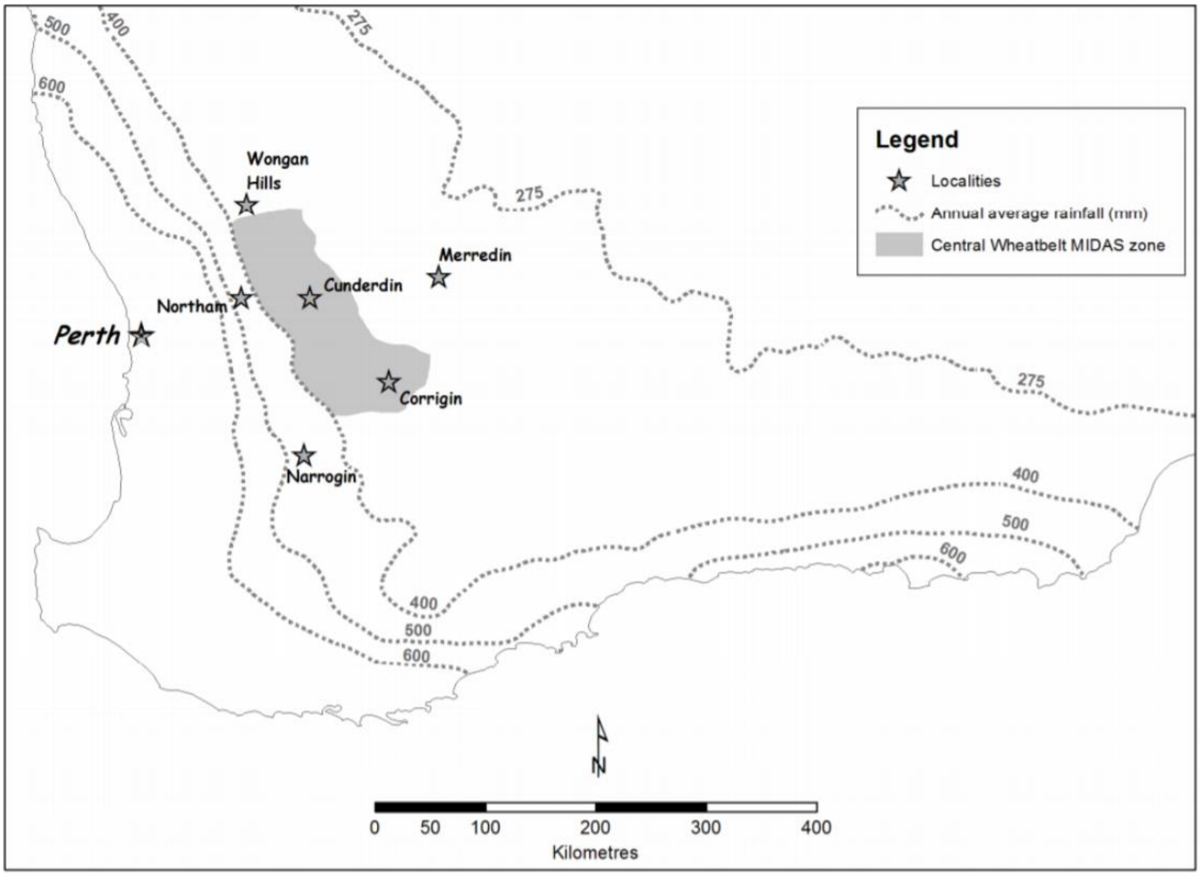

Figure 2. Map of Central Wheatbelt region.

As a steady state, deterministic linear programming model based on an average weather-year within the Central Wheatbelt, MIDAS cannot account for the transition to equilibrium, seasonal variability or the uncertainty surrounding the loss of glyphosate and paraquat for farmers with different risk preferences. In this study what is forgone is the ability to undertake a dynamic assessment. Nonetheless, the biological complexity of the farming system captured in MIDAS does allow the key likely strategic impacts of loss of glyphosate and paraquat to be characterised.

The MIDAS model for the study region (Figure 2) has a long history of use; its most recent update and re-validation being undertaken by Thamo *et al.* (2017). MIDAS is structured as several hundred activities that include alternative rotations on each of eight land management units (see Table 3), crop sowing opportunities, feed supply and feed utilisation by different livestock classes, yield penalties for delays to sowing, cash flow recording and machinery and overhead expenditures. The model's solution is the subset of activities that draws on farm resources, subject to a range of constraints, to generate maximum profit. Constraints include resource limits (e.g. areas of each LMU, machinery work rates, time restrictions on seeding and harvesting), technical constraints (e.g. representing the demand for, and supply of, animal feed), logical constraints (e.g. flows of sheep classes that determine flock structure (see Young *et al.* 2020)) and financial accounting constraints such as limits on borrowings.

4.2 Development of no glyphosate, and no glyphosate and paraquat farm system scenarios

Through on-line interactions and discussions with farmers, agronomists, farm management consultants, and weed scientists, various options available to farmers were identified, if use of glyphosate, and then glyphosate and paraquat was restricted. Due to COVID restrictions and availability of particular experts, the collation, interaction and review of interviewee suggestions and opinions needed to be virtual. From these interactions, scenarios were developed of the likely management reactions if glyphosate, and then glyphosate and paraquat were no longer available for use.

4.3 Assumptions made in the MIDAS analysis

4.3.1 Commodity price changes

A crucial assumption underpinning the assessment of impacts of loss of access to glyphosate, and then paraquat, is how widespread is the ban on these chemicals. One possible scenario is that Australia follows the lead of some European and Gulf countries and bans use of these chemicals, whilst other major grain-producing and exporting countries maintain use of these chemicals. Under this scenario, world prices of traded grains would not greatly change as these prices are principally influenced by the volumes of GT crops grown in North and South America. The ramification would be that farm-gate prices received by farms in the central wheatbelt of WA would be largely unaffected solely by a domestic ban on use of these chemicals as about 90% of grain produced in that region is exported.

However, if a global ban applied, then as outlined by Brookes *et al.* (2017), regions of the world dependent on production or purchase of GT crops (e.g. corn and soybean) would be especially disadvantaged. Brookes et al. (2017)'s general equilibrium modelling analysis of a global glyphosate ban identified the most severely affected countries were USA, Argentina and Brazil, due to their reliance on GT crops. According to their analyses, a global inability to produce or purchase GT crops, due to a ban on use of glyphosate, would lead to an increase in all world crop prices, wheat price would increase by 40% and coarse grains (i.e. barley) prices would increase by 140%. Currently, it is unlikely that governments and industry in North and South America would agree to a universal ban on these herbicides.

Hence, the scenario more likely to unfold is greater restrictions on use of these chemicals in Australia that would leave farm-gate commodity prices largely unchanged. This price scenario underpins most of the analyses presented later in this thesis. However, for the sake of completeness, the less plausible alternate price scenario is also briefly considered whereby global grain prices increase due to an international ban on these herbicides.

4.3.2 No glyphosate tolerant genetically modified canola

It was assumed under the loss of glyphosate GT canola would no longer be grown, as the seeds are expensive and the benefit the technology provides would no longer be realised. The non-GT canola variety selected within MIDAS is triazine tolerant canola.

4.3.3 Change in herbicide applications

The unchanged, base herbicide options in MIDAS include a range of herbicides for knock downs, pre-emergent spraying and post emergent spraying. Within these unchanged herbicide options, glyphosate is used as a knockdown, and paraquat is used for spray topping as well as a knockdown in conjunction with the active ingredient diquat within the herbicide Sprayseed 250. The unchanged MIDAS herbicide options are presented in the appendix.

It was assumed that the herbicides applied, or herbicide options, would alter if glyphosate were no longer available. The no glyphosate herbicide options modelled in MIDAS are presented in the appendix. Glyphosate knock downs would be replaced with a knock of paraquat and Pyresta, a group I herbicide with the active ingredients Pyraflufen and 2,4-D ethylhexyl ester.

The herbicide options were changed again under the scenario of both glyphosate and paraquat no longer being available for use. The no glyphosate and no paraquat herbicide options are presented in the appendix. Knock downs with paraquat were primarily used for summer fallow weed management. These summer weeds under this scenario were instead controlled through sprays of Pyresta for grass weeds and Afghan melon control, sprays of Garlon, a group I herbicide, for Paddy melon control and sprays of Basta, a group N herbicide. Basta with the active ingredient Glufosinate-Ammonium is the herbicide chosen to replace paraquat as it has similar control to paraquat although it is more expensive and has temperature requirements (i.e. it must be applied at temperatures below 33°C with humidity above 50%) which restrict the times it can be applied. The herbicides Sharpen WG and Reglone, with active ingredients Saflufenacil and Diquat, respectively, would be used for spray topping instead of paraquat. Sharpen WG is a group G herbicide and Reglone is a group L herbicide.

MIDAS does not represent all the technical minutiae of herbicide choice, which is the province of agronomic advice; MIDAS represents the financial consequences of herbicide selection through a single aggregated cost of herbicides per hectare. Hence, the alteration in herbicide selection is represented in MIDAS as changes in the aggregate cost of herbicide use in different rotations on different land management units.

4.3.4 Harvest with HWSC technology

The consensus among all discussion participants was that farmers' adoption of HWSC technology (Walsh *et al.* 2013; Jacobs and Kingwell 2016; GRDC 2018; Harries *et al.* 2020) would become essential in the absence of glyphosate and paraquat. HWSC is an umbrella term covering a range of technologies and practices that capture and destroy weed seeds at harvest. These include chaff carts, narrow windrow burning, chaff lining, chaff tramlining and weed seed impact mills towed or combined within a grain harvester. The HWSC option modelled was the Harrington seed destructor (Vertical iHSD, HSD (2020)) involving a $92,000 capital cost with a variable cost of $8.93 per crop hectare. Harries *et al.* (2020) identified that HWSC, even under current circumstances, is likely become a key weed management strategy for farmers over the next several years.

4.3.5 Increased nitrogen application

It was assumed that due to the loss of glyphosate, there would be increased summer weed populations. The control of summer weeds has been found to increase nitrogen availability for plant uptake by 89% (Haskins and Mcmaster 2012). Summer weeds use stored soil moisture and nitrogen, control of summer weeds ensures access to plant available water and nitrogen for the subsequent crop (Haskins and Mcmaster 2012). Without glyphosate, summer weed control would be more difficult as the use of the double knock down method with glyphosate would no longer be available. Weed control would become increasingly difficult if paraquat was also no longer available. Increased prevalence of summer weeds would reduce plant available nitrogen and water for the upcoming crop. Plant available water also increases nitrogen mineralisation, which makes nitrogen available for use by plants (Haskins and Mcmaster 2012). Failure to control summer weeds, due to the loss of these herbicides, would result in less plant available nitrogen and increased application of nitrogen at seeding. To account for this in MIDAS, a sensitivity analysis of increased nitrogen fertiliser application was conducted, where herbicide options have been altered and HWSC technology is applied under the base case of this analysis.

4.3.6 Grazing of crop area between break of season and subsequent planting

A sensitivity analysis on the proportion of crop area grazed between break of season and first rains was conducted to reflect how grazing intensity could be adjusted to facilitate weed control in the absence of glyphosate and paraquat. This period, between the break of season and subsequent planting, occurs in autumn to late autumn.

4.3.7 Delayed seeding

Uncontrolled summer weed populations, as a result of the loss of glyphosate and paraquat, could cause seeding timing to be delayed. Uncontrolled summer weeds can cause seeding machinery blockages delaying the timing of seeding. Summer weed populations require applications of herbicides to control these weeds before seeding. If glyphosate and paraquat cannot be used then seeding delays can occur if mechanical weed control is needed. Also, paddocks previously dry sown but now, due to the loss of the glyphosate and paraquat, have weeds present will consequently not allow these paddocks to be dry sown, again causing a delay in seeding. The potential delays to seeding necessitate various additional actions of farmers are described below.

4.3.8 Purchase of an additional seeder

As mentioned previously, were glyphosate and subsequently paraquat no longer available, summer weed control may be less effective. There would be more areas of the farm with summer weeds present, and this would limit the proportion of the farm available to be dry sown. Consequently, compression of the period of seeding would occur, necessitating purchase of an additional seeder. The capital cost of $190,000, as well as the variable costs of repairs and maintenance, labour and fuel of the additional seeder totalling $9.23 per hectare, were modelled on cropping hectares.

4.3.9 Purchase of an additional sprayer

The purchase of an additional sprayer is based on the assumption that loss of glyphosate and paraquat would cause summer weed control to be less effective and therefore more weeds would be present at the break of season. An extra spray, or ‘knock’ would be required to control these summer weeds, and this additional knock would need to take place in the short window between the break of season and seeding. The purchase of an additional sprayer was modelled to enable this spraying to take place without affecting the timing of seeding. Were a farmer not to have the spraying machinery capacity to undertake the additional herbicide applications the purchase of an additional sprayer would be necessary and was therefore modelled. The capital cost of $70,000, as well as its variable costs of repairs and maintenance, labour and fuel totalling $6.08 per hectare were included.

This analysis was conducted as an optional management change, after the addition of all other management changes. A WA farm survey conducted by Harries *et al*. (2020) found that farmers used an average of 6.3 herbicide applications per paddock per year. Therefore, many farmers likely already have the machinery capacity to apply additional sprays of herbicides to replace to loss of glyphosate, and the loss of glyphosate and paraquat.

4.3.10 Lower yields

A sensitivity analysis on yield reduction was modelled under the assumption that despite all the additional weed control, weed populations would still present problems across the farm. The presence of weeds limits potential yields of all species grown, crops and pastures.

4.4 Using MIDAS to model farm performance

MIDAS was altered to incorporate the farm management actions presented above. To ensure model results were credible and error-free, preliminary results were discussed with agronomists, weed scientists and farm management consultants. Their feedback led to some recalibration, and some adjustments in the modelling.

Changes in the input costs of crop and sheep enterprises, changes to crop and livestock enterprises, changes to on-farm emissions production and changes to farm profit were analysed for the range of management changes occurring under the two main scenarios: loss of glyphosate, and loss of glyphosate and paraquat.

All management changes were applied to three farm types that had varying proportions of soil types found in the study region. These farms are defined as a predominantly light (i.e. sandy) soils farm, a predominantly heavy (i.e. clay and clay loams) soils farm, and an average central wheatbelt farm (see Table 2). The soil characteristics for each LMU are listed in Table 3.

Table 2. Table of areas the land management units (LMUs) on the farms central wheatbelt, predominantly light and predominantly heavy.

	Land management units								
	1	2	3	4	5	6	7	8	
Farm type	Areas of land management units (ha)								Farm size (ha)
Central wheatbelt	260	400	650	400	375	375	565	725	3750
Predominantly light soils	445	585	840	400	375	95	280	730	3750
Predominantly heavy soils	70	210	470	400	375	655	845	725	3750

Table 3. Table of descriptions of each land management unit (LMU) in MIDAS.

LMU	Name	Description
1	Poor sands	Poor moisture and nutrient availability limits crop and pasture growth.
2	Average sandplain	Poor moisture and nutrient availability limits cereal growth.
3	Good sandplain	Produces high cereal, lupin and pasture yield.
4	Shallow duplex	Good moisture and nutrient availability.
5	Medium heavy soils	Generally good moisture and nutrient availability although limited in dry periods, produces good cereal, lupin and pasture growth.
6	Heavy valley	Good cereal, field pea and pasture production, often limited by soil structure decline and salinity.
7	Sandy surfaced valley	Produces good cereal, lupins and pasture production.
8	Deep duplex soils	Good moisture and nutrient availability producing good plant growth.

A number of scenarios were considered to test the two hypotheses of this study. The base case scenario was that each farm type under examination (i.e. average farm, light land farm, heavy land farm), maintained access to glyphosate and paraquat. A range of scenarios then were examined against each base case. The number of scenarios that underpin the results presented in section 5 are the factorial combination of 3 farm types and 7 combinations of herbicide restrictions (e.g. no glyphosate and, no glyphosate and no paraquat) and management responses (e.g. HWSC, purchase of an additional seeder, then sprayer, increased nitrogen applications, increased grazing after the break of season). In short, there are $3 \times 7 = 21$ scenarios; plus the impacts of a global ban on glyphosate and paraquat for the average farm involving 5 levels of possible increases in grain prices are considered. Hence, a total of $21 + 5 + 3 = 29$ scenarios are examined, where the last 3 are the base cases for each farm type.

To economise on space, only main results are presented and not every scenario has its results presented. For example, the scenarios of loss of access to glyphosate only are not reported here. Rather the starting point for display of results is the scenario where glyphosate and paraquat both can no longer be used. Details of the loss of access to glyphosate only are presented in the appendix.

5. Results

To understand how the study region's farming systems might change in response to loss of glyphosate and paraquat, analyses were conducted for the three different farm types: (1) an average central wheatbelt farm, (2) a predominantly heavy soils farm, and (3) a predominantly light soils farm. All farms were the same arable area.

For each farm type, the base case of continued access to glyphosate and paraquat was compared against a series of management changes described earlier in section 4.3. The base case land use rotation selections are presented in the appendix, as are the model's price assumptions for main farm products such as grains, sheep and wool. The herbicide options for each crop phase when glyphosate and paraquat are both available, glyphosate is not available and when both glyphosate and paraquat are not available are also presented in the appendix. The following sub-sections consider each farm type in turn and describe how the cascade of management responses to loss of the herbicides alters optimal farm plans.

5.1 Average central wheatbelt farm

When glyphosate and then both glyphosate and paraquat are not available and the farmer is required to undertake a capital investment in harvest weed seed control (HWSC) then, farm profit decreases by $48,058, (12.8%) and herbicide costs increase (Table 4). Crop area falls by 42 ha, annual pasture area increases by 220 ha, and sheep numbers increase by 80 DSE (Table 4). Not listed in table 4 is the area of perennial pasture (lucerne) that decreases by 183 ha, allowing the area of annual pasture area to increase more than the reduction in crop area. Rotational changes occur on LMUs 2, 7 and 8 and total farm emissions reduce by 11 t CO_2e when paraquat is also no longer available for use, as reductions in emissions production from crop residues and nitrogen fixation emissions reduce by a greater proportion than increases in sheep emissions. Note that farm profit in MIDAS is defined as net cash returns minus non-cash costs and minus the opportunity cost of capital (exclusive of land).

Table 4. Impacts on the average central wheatbelt farm of HWSC, and herbicide options altered to adapt to the loss of glyphosate, and then loss of both herbicides, glyphosate and paraquat.

	Herbicide cost ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total (t CO_2e)	Farm profit ($)
No glyphosate with HWSC	200,468	2,261	1,086	12,362	3,365	376,468
No glyphosate and paraquat with HWSC	221,712	2,219	1,306	12,442	3,354	328,410

Increased demand for the herbicides which replace the use of glyphosate and paraquat will result in economies of scale benefits to the production of these herbicides as demand for these herbicides increases, resulting in a potential decline in their prices. However, when glyphosate and paraquat are no longer available and HWSC technology is applied, a 40% decline in the prices of the herbicides used in place of glyphosate and paraquat is required to ensure the resulting farm profit ($360,834 in Table 5) is nearly equal to the farm profit under the scenario of no glyphosate and paraquat (Table 5). Such a drop in prices of alternative herbicides is unlikely. Furthermore, usually an increase in demand for a product, such as a herbicide, is mostly associated with upward pressure on its price, not a large reduction in its price. Although the alternatives to glyphosate and paraquat are modelled with a 40% price drop the total expenditure on use of all herbicides only declines by about 10%.

Table 5. Impacts of no glyphosate and paraquat, the impacts of no glyphosate and paraquat with HWSC technology, and the impacts of a herbicide price drop of 40% on herbicides used to replace glyphosate and paraquat, when glyphosate and paraquat are no longer available and HWSC technology is applied.

	Herbicide cost ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total (t CO_2e)	Farm profit ($)
NGNP[1]	230,153	2,274	1,200	12,339	3,342	361,007
NGNP[1]+HWSC	221,712	2,219	1,306	12,442	3,354	328,410
NGNP[1]+HWSC and 40% reduced prices of herbicide alternatives	207,634	2,261	1,069	12,364	3,282	360,834

[1] NGNP=No glyphosate and no paraquat

If the farmer is required to apply more nitrogen fertiliser to make up for nitrogen lost to summer weeds not able to be easily controlled due to loss of glyphosate and paraquat, then farm profit decreases further (Figure 3). Crop and annual pasture areas demonstrate an inverse relationship as the percentage of additional nitrogen fertiliser increases, with crop area falling overall by 92 ha, (4%) whilst annual pasture area increases by 92 ha, (7%). Rotational changes occur on LMUs 2 and 7. Farm profit falls by $38,064, (13%) over the whole analysis with increases in fertiliser costs accounting for 97% of the decrease in farm profit.

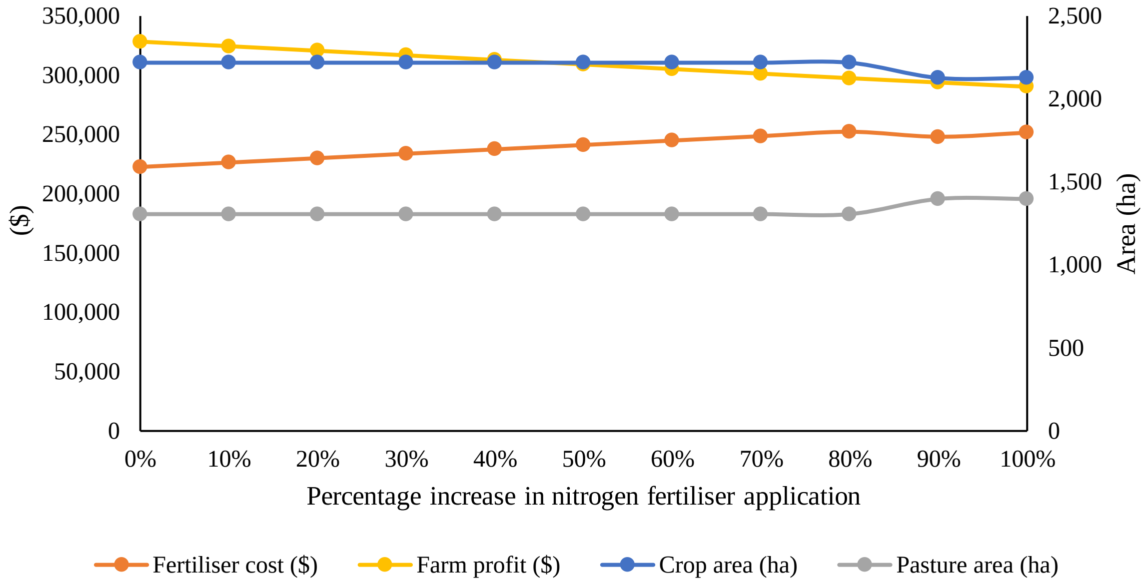

Figure 3. Impacts on fertiliser costs, farm profit, crop and annual pasture area with proportional increases in nitrogen application when glyphosate and paraquat are no longer available on the average central wheatbelt farm.

A further management tactic is to graze crop paddocks between the break of season and seeding. If 100% of crop paddocks are grazed between the break of season and seeding, supplementary feed costs increase by $7,057 and farm profit falls by $78,738, (24%) compared to no crop paddocks grazing at this time (Figure 4). Crop area decreases overall by 294 ha and annual pasture area increases by 294 ha. Land use changes occur on LMUs 2 and 7.

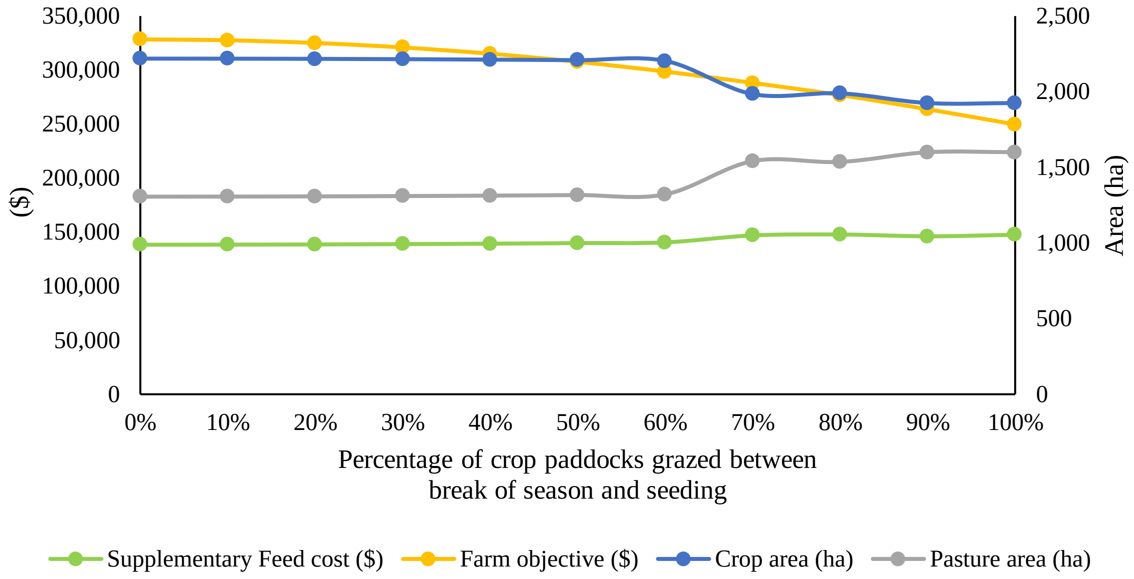

Figure 4. Impacts on farm profit, crop and annual pasture area, and supplementary feed cost with an increasing percentage of crop paddocks being grazed between break of season and seeding on the average central wheatbelt farm.

Another ramification of loss of glyphosate and paraquat is that uncontrolled summer or poorly controlled weed populations limit the area available to be dry sown on farm. When lupins and canola can no longer be dry sown, farm profit decreases by $12,375, (3.8%) (Table 6). Both crop and annual pasture area decrease, but the area of lucerne increases to enable a lift in sheep numbers (Table 6). Rotational changes occur on LMUs 2, 4 and 7. Rotational changes on LMU 2 involved a continuous pasture rotation changing to continuous cropping rotation. Continuous cropping rotation on LMU 4 changed to cropping and annual pasture rotation, and on LMU 7 changes involved removal of a wheat phase from wheat and pasture rotation. Despite the slightly larger sheep flock overall emissions are slightly less due to less nitrogen fixation as less area is in pasture and less fertiliser is used due to the decline in the crop area.

Table 6. Impacts on crop and annual pasture area, sheep numbers in May, farm emissions and farm profit when either dry seeding or no dry seeding of canola and lupins occur on the average central wheatbelt farm.

	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
Dry seeding	2,219	1,306	12,442	3,354	328,410
No dry seeding	2,159	1,188	12,553	3,340	316,035

Another tactic is to purchase an additional seeder in response to loss of glyphosate and paraquat but this leads to farm profit falling by $33,827, (11%) (Table 7). Crop area decreases by 32 ha, and both annual pasture area and sheep numbers increase. The area of lucerne decreases by 178 ha, accounting for the difference in the change of crop and annual pasture area. Land use changes occur on LMUs 2, 4 and 7.

Table 7. Impacts of no dry seeding, the purchase of an additional seeder, and purchase of an additional seeder and sprayer on the average central wheatbelt farm.

	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
No dry seeding	2,159	1,188	12,553	3,340	316,035
Additional seeder	2,127	1,398	12,613	3,340	282,197
Additional seeder and sprayer	1,980	1,545	12,886	3,395	260,208

After purchase of an additional seeder, another management tactic is to purchase an additional sprayer but this causes farm profit to fall by $21,989, (8%), and crop area declines by 147 ha as the inclusion of an additional sprayer increases the cost per hectare of cropping (Table 7). Annual pasture area and sheep numbers increase and rotational changes occur on LMUs 2 and 7.

Whole farm emissions do not change when an additional seeder is purchased but purchasing an additional sprayer is associated with farm emissions increasing by 55 t CO_2e, most of which results from increased sheep and nitrogen fixation emissions.

Lastly, a sensitivity analysis of reducing the potential yield of all crop and pasture species was undertaken to represent the impact of uncontrolled or poorly controlled weed populations, despite the range of management tactics adopted (Figure 5). This analysis was undertaken as some farm advisers were pessimistic about the likelihood of farmers being able to control weed populations, despite farmers embracing a range of additional weed control measures in the absence of glyphosate and paraquat. Under this pessimistic outlook farm profit declines by an average of $16,851 per 2% reduction in maximum yield of all crop and pasture species. Overall farm profit decreases by $84,257, (32%), when a 10% yield reduction is assumed. Crop area decreases across the 0% to 10% yield reduction by 87 ha, (4.3%) and annual pasture area increases by 87 ha. Rotational changes occur on LMUs 2 and 7.

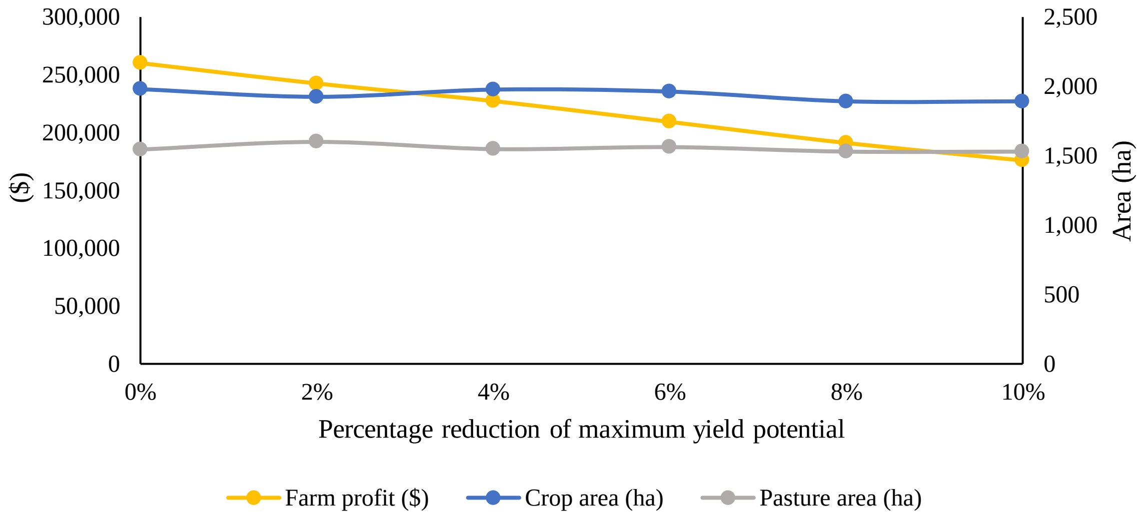

Figure 5. Impacts on farm profit, crop and annual pasture area, with reducing potential yields of all crop and pasture species by 2% increments on the average central wheatbelt farm.

Table 8 summarises the cumulative impacts of the various management changes described above in response to the prohibited use of glyphosate and paraquat. When these herbicides are no longer available and alternative weed control measures and farming system adjustments are required, then the main impact is a large decline in farm profit and a slight shift away from cropping into more sheep production. The decline in profit is caused by increased expenditure on weed control via the purchase of new machinery (e.g. HWSC or an extra sprayer), increased outlays on additional herbicides and by reduced crop and pasture yields. The land use changes where areas of cropping become areas of pasture generally occur on LMUs 2 & 7. Rotational choices in the base case, no glyphosate, and no glyphosate with the inclusion of HWSC technology are presented in the appendix.

Table 8. Summary table of the impacts of the loss of glyphosate and paraquat on farm profit, crop area (as a percentage of the whole farm area), herbicide costs, fertiliser costs, sheep number, LMUs on which land use change occurred and emissions from the average central wheatbelt farm.

	Farm profit ($'000)	Crop %	Herbicide cost ($'000)	Fertiliser cost ($'000)	Sheep in May (DSE)	LMU land use change	Emissions (t CO2e)
Base case (glyphosate + paraquat are available)	430	60.3	178	227	12,364		3,291
No glyphosate	410	60.3	201	227	12,364	No change	3,302
No glyphosate + HWSC	376	60.3	200	227	12,362	7 & 8	3,364
NGNP[1] + HWSC	328	59.2	222	223	12,442	2, 7 & 8	3,354
NGNP[1] + HWSC + Extra N	290	56.7	215	252	12,612	2 & 7	3,336
NGNP[1] + HWSC + no dry seeding	316	57.6	242	219	12,553	2, 4 & 7	3,340
NGNP[1] + HWSC + dry seeding + Extra seeder	282	56.7	215	218	12,613	2, 4 & 7	3,340
NGNP[1] + HWSC + dry seeding + Extra seeder and sprayer	260	52.8	201	210	12,886	2, 4 & 7	3,395
NGNP[1] + HWSC + dry sowing + Extra seeder and sprayer + 10% yield decline	176	50.5	196	188	13,048	2 & 7	3,363

[1] NGNP=No glyphosate and no paraquat

Note: Change in time of sowing is not included as land use change.

5.2 Predominantly light soils farm

When glyphosate and then glyphosate and paraquat are not available and both scenarios have HWSC technology applied on farm then the key impacts are as listed in Table 9. Farm profit falls by $49,674, (15%) and herbicide costs increase by $37,512. Crop and annual pasture areas, sheep numbers and emissions change little. These land use changes occur on LMUs 3, 5 & 8.

Table 9. Impacts of loss of glyphosate, and then glyphosate and paraquat on farm profit, crop and annual pasture areas, sheep number and emissions on the predominantly light soils farm

	Herbicide cost ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO$_2$e)	Farm profit ($)
No glyphosate with HWSC	182,956	2,064	1,254	12,730	3,392	330,652
No glyphosate and paraquat with HWSC	220,468	2,063	1,254	12,731	3,370	280,978

As was the case in the analysis for the average farm, a decline in the prices of the herbicides which replace glyphosate and paraquat was examined. A 37.5% price drop in the prices of those herbicides is required to ensure no change in farm profit between the scenario no glyphosate and paraquat with HWSC technology and the scenario of no glyphosate and paraquat without HWSC technology (Table 10).

Table 10. Impacts of no glyphosate and paraquat, the impacts of no glyphosate and paraquat with HWSC technology, and the impacts of a herbicide price drop on herbicides used to replace glyphosate and paraquat, when glyphosate and paraquat are no longer available and HWSC technology is applied on the predominantly light soils farm.

	Herbicide cost ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total (t CO$_2$e)	Farm profit ($)
NGNP[1]	220,532	2,064	1,254	12,730	3,372	311,691
NGNP[1]+HWSC	220,468	2,063	1,254	12,731	3,370	280,978
NGNP[1]+HWSC 37.5% reduced herbicide alternatives	190,845	2,064	1,254	12,730	3,372	311,491

---

[1] NGNP = No glyphosate and no paraquat

Uncontrolled summer weed populations use plant available nitrogen, so a sensitivity analysis increasing the percentage of nitrogen applied at seeding was conducted (Figure 6). Farm profit decreases by $37,126, (11.6%) from the 0% to 100% increase in nitrogen application (Figure 6). From the 0% to 100% increase in nitrogen application, crop area increases by 152 ha, (7%). Annual pasture area is more sensitive to changes in nitrogen fertiliser application than crop area with the annual pasture area increasing by 404 ha, (24%) over the analysis. The area of lucerne, a perennial pasture, decreases over this analysis, the sum of the changes in area of lucerne and crop equal the change in area of annual pasture. Rotational changes occur on LMUs 2, 5 and 8. Fertiliser costs increase by $23,258 between the 0% and 100% increase in nitrogen fertiliser application.

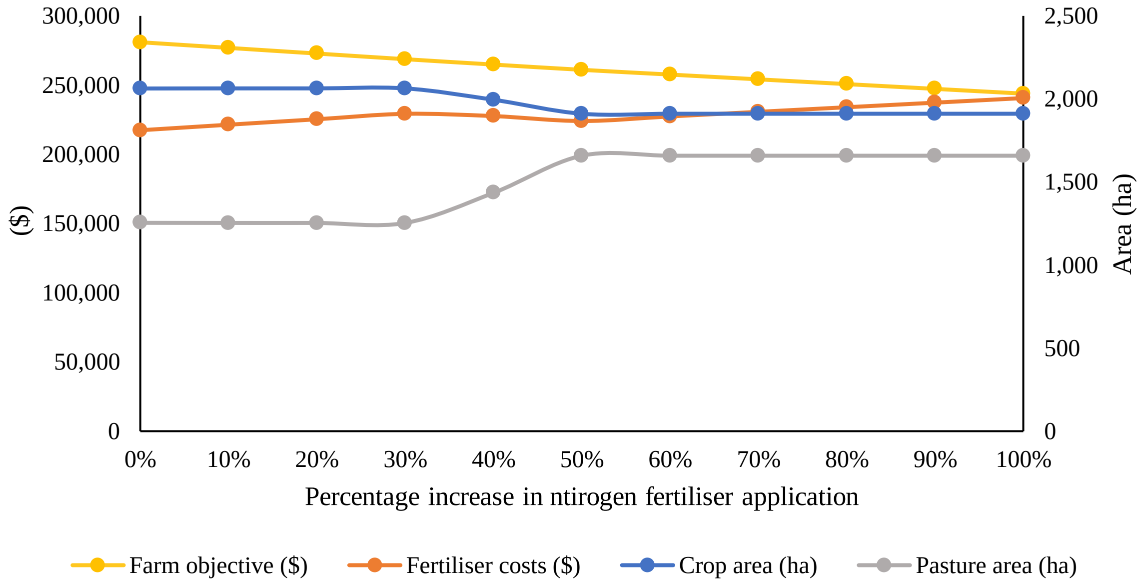

Figure 6. Impact on fertiliser costs, farm profit, crop and annual pasture area with increases in nitrogen applications when glyphosate and paraquat are not available on the predominantly light soils farm.

A sensitivity analysis was conducted adjusting the percentage of crop paddocks grazed between break of season and seeding in order to represent the tactic of sheep grazing summer weeds (Figure 7). Over the whole range of paddock grazing (i.e. 0% to 100%) farm profit falls by $74,457, (26%) (Figure 7). By contrast, supplementary feed costs increase by $15,140, crop area decreases by 282 ha whilst annual pasture area increases by 328 ha. The area of lucerne decreases by 46 ha. Land use changes occur on LMUs 2, 5 and 8.

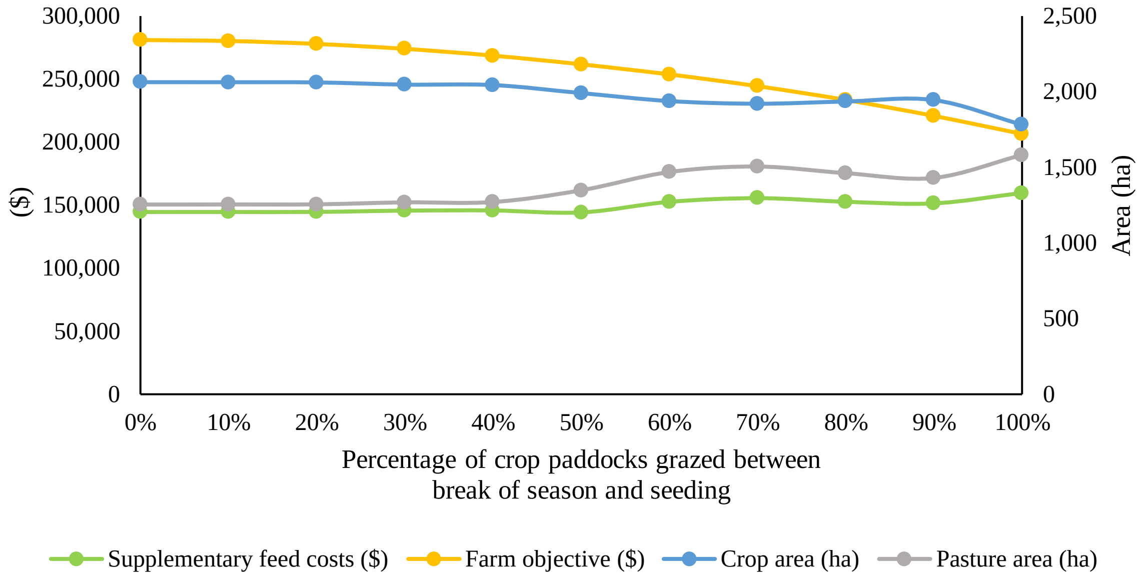

Figure 7. Impacts on farm profit, crop and pasture area and supplementary feed cost as an increasing percentage of crop paddocks are grazed between the break of season and seeding on the predominantly light soils farm.

As stated in a previous sub-section, uncontrolled summer weed populations limit the area available to be dry sown. When dry seeding of canola and lupins is constrained to 0 hectares, the model results can be compared to the case where dry seeding is unconstrained (Table 11). Farm profit falls by $7,009, (2.5%); crop area decreases by 116 ha and annual pasture area and sheep numbers increase by 57 ha and 216 DSE, respectively. The area of lucerne increases by 59 ha, accounting for the difference in crop and annual pasture area change. All rotational changes occur on LMUs 2, 4, 5 and 8. Emissions are slightly less due to the smaller sheep population and less use of fertiliser due to the decline in the crop area.

Table 11. Impacts on crop and annual pasture area, sheep numbers, emissions and farm profit for unconstrained and constrained dry seeding on the predominantly light soils farm.

	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
Dry seeding	2,063	1,254	12,731	3,335	280,978
No dry seeding	1,947	1,311	12,947	3,330	273,969

The tactic of purchase of an additional seeder required to combat loss of the opportunity to dry sow unfortunately further lowers farm profit (Table 12) by $36,695, (13%). Annual pasture area and sheep numbers increase by 146 ha and 22 DSE, respectively. Lucerne area decreases by 134 ha allowing for the change in pasture area to be greater than crop. Land use changes occur on LMUs 2, 4 and 8.

Table 12. Impacts on crop and pasture area, sheep numbers, emissions and farm profit on the predominantly light soils farm with no dry seeding, the purchase of an additional seeder, and purchase of an additional seeder and sprayer.

	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
No dry seeding	1,947	1,311	12,947	3,335	273,969
Seeder	1,935	1,457	12,969	3,309	237,274
Seeder and sprayer	1,865	1,640	13,100	3,322	216,766

The tactic of purchase of an additional sprayer was also modelled where the farmer did not have the machinery spraying capacity for the additional herbicide sprays required to control summer weeds under the loss of both glyphosate and paraquat (Table 12). Farm profit falls by $20,508, (9%) and crop area declines by 70 ha. Pasture area increases by 183 ha, lucerne area decreases by 113 ha and sheep numbers increase by 131 DSE. Emissions alter little and land use changes occur on LMUs 2 and 8.

Responding to farm advisers' pessimism about farmers' abilities to control weeds in the absence of glyphosate and paraquat, a sensitivity analysis was conducted that reduced crop and pasture yields (Figure 8). Crop area decreases by 236 ha, (13%) and pasture area decreases by 31 ha, (2%), when all crop and pasture yields decrease from 0% to 10% (Figure 8). Over the range of analysed yield reductions, the area of lucerne increases by 267 ha. All rotational land use changes occur on LMUs 2, 4, 5 and 8 and farm profit falls by an average of $15,475 per 2% reduction in crop and pasture yields, overall decreasing by $77,374, (36%).

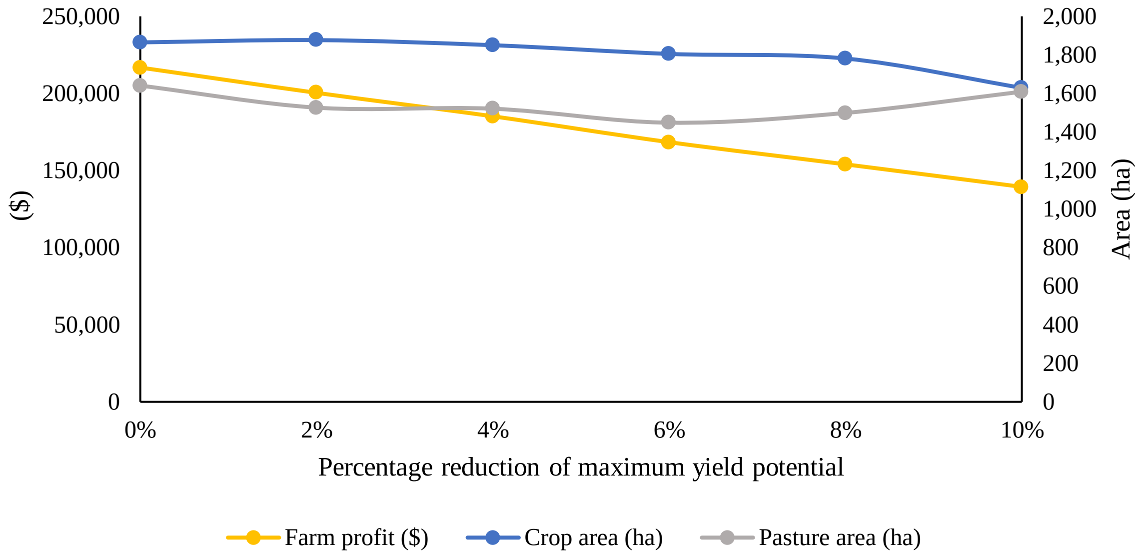

Figure 8. Impacts on farm profit, crop and annual pasture area, under a sensitivity analysis that reduces potential yields of all crop and pasture species by 2% increments on the predominantly light soils farm.

Table 13 summarises the cumulative impacts of the various management changes described above in response to the prohibited use of glyphosate and paraquat on the light land farm. Crop area percentage decreases from 55.1% to 43.4% over the range of analysed farm management changes and farm profit falls by $240,000. When these herbicides are no longer available and alternative weed control measures and farming system adjustments are required, then the main impact is a large decline in farm profit and a slight shift away from cropping into more sheep production. This land use change of a move from cropping to sheep production generally occurred LMUs 2, 5 & 8. The decline in profit is caused by increased expenditure on weed control via the purchase of new machinery (e.g. HWSC or an extra seeder or sprayer), increased outlays on herbicides; and by reduced crop and pasture yields. Rotational choices on each LMU are presented in the appendix for the base case, and for the scenarios of no glyphosate and no glyphosate with HWSC technology.

Table 13. Summary table of the impacts of the loss of glyphosate and paraquat on farm profit, crop area as a percentage of the whole farm, herbicide costs, fertiliser costs, sheep number, LMUs on which land use change occurred and emissions on the predominantly light soils farm.

	Farm profit ($’000)	Crop %	Herbicide cost ($’000)	Fertiliser cost ($‘000)	Sheep in May (DSE)	LMU land use change	Emissions (t CO2e)
Base case with glyphosate & paraquat	379	55.1	165	218	12,722		3,386
No glyphosate	361	55.0	183	217	12,730	2, 5 & 8	3,392
No glyphosate + HWSC	331	55.0	183	217	12,730	No change	3,392
NGNP[1] + HWSC	281	55.0	220	217	12,731	3, 5 & 8	3,370
NGNP[1] + HWSC + Extra N	241	50.9	190	241	13,014	2, 5 & 8	3,411
NGNP[1] + HWSC + no dry seeding	274	51.9	223	207	12,947	2, 4, 5 & 8	3,330
NGNP[1] + HWSC + dry seeding + Extra seeder	237	51.6	204	207	12,969	2, 4 & 8	3,309
NGNP[1] + HWSC + dry seeding + Extra seeder and sprayer	217	49.7	190	203	13,100	2 & 8	3,322
NGNP[1] + HWSC + dry seeding + Extra seeder and sprayer + 10% yield decline	139	43.4	178	175	13,538	2, 4, 5 & 8	3,429

[1] NGNP=No glyphosate and no paraquat

Note: Change in time of sowing is not included as land use change.

5.3 Predominantly heavy soils farm

Under the scenarios of no glyphosate or no glyphosate and no paraquat, HWSC technology is introduced to facilitate weed control, yet farm profit falls by $48,777, (12.1%) (Table 14). Crop and pasture areas and sheep numbers do not alter and herbicide costs increase by $36,859. This land use changes occur on LMUs 2 and 3. Emissions slightly decline mostly due to slightly lower crop and pasture biomass and their associated emissions via crop residues and nitrogen fixation.

Table 14. Key impacts on the predominantly heavy soils farm of no access to glyphosate and or paraquat, assuming HWSC is used in all cases.

	Herbicide cost ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
No glyphosate + HWSC	201,415	2,306	1,219	12,280	3,290	404,125
No glyphosate and paraquat + HWSC	241,274	2,306	1,219	12,280	3,270	355,348

As was the case in the analysis for the average farm, a decline in the prices of the herbicides which replace glyphosate and paraquat was examined. A 50% price drop in the prices of those herbicides is required to ensure no change in farm profit between the scenario no glyphosate and paraquat with HWSC technology and the scenario of no glyphosate and paraquat without HWSC technology (Table 15).

Table 15. Impacts of no glyphosate and paraquat, the impacts of no glyphosate and paraquat with HWSC technology, and the impacts of a herbicide price drop on herbicides used to replace glyphosate and paraquat, when glyphosate and paraquat are no longer available and HWSC technology is applied on the predominantly heavy soils farm.

	Herbicide cost ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total (t CO_2e)	Farm profit ($)
NGNP[1]	241,274	2,306	1,219	12,280	3,372	389,267
NGNP[1]+HWSC	241,274	2,306	1,219	12,280	3,270	355,348
NGNP[1]+HWSC 50% reduced herbicide alternatives	199,015	2,306	1,254	1,219	3,270	398,784

[1] NGNP = No glyphosate and no paraquat

A sensitivity analysis on nitrogen application to represent loss of soil nitrogen through uptake by summer weeds (Figure 9) reveals a decrease in crop area by 58 ha, (2.5%) and pasture area increases by 58 ha, (4.5%) from a 0% to 100% increase in nitrogen application. From the 0% to 100% proportional increase in nitrogen application, farm profit falls by $40,890, (11.5%), and increased fertiliser costs account for 71% of the reduction in farm profit.

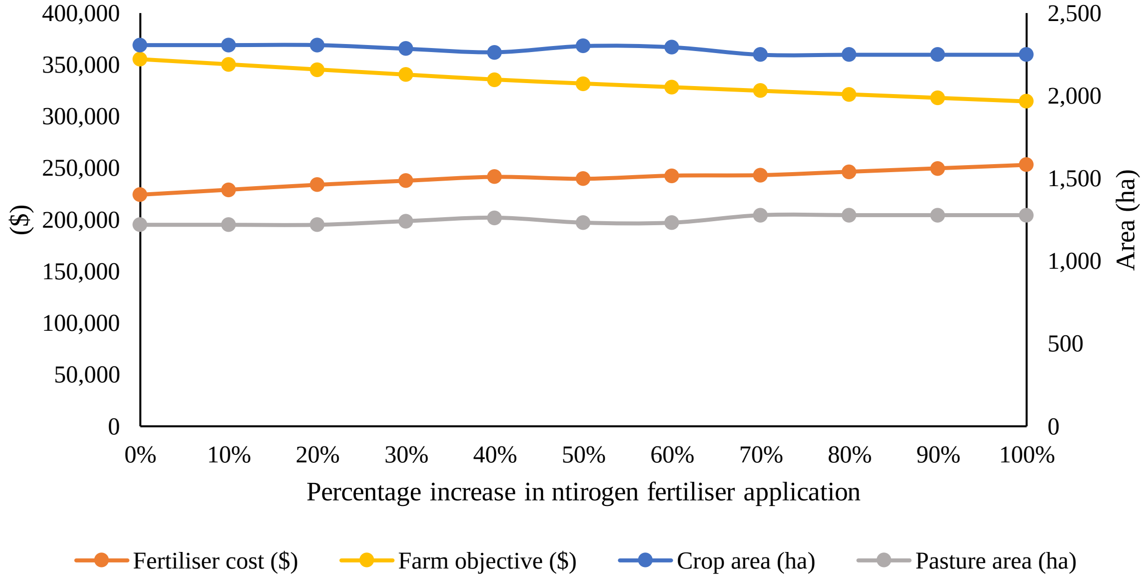

Figure 9. Impacts on farm profit, crop and annual pasture area, as the proportional increase in nitrogen application was applied when glyphosate and paraquat were not available on the predominantly heavy soils farm.

A sensitivity analysis was conducted adjusting the percentage of crop paddocks grazed between break of season and seeding in order to represent the tactic of sheep grazing summer weeds (Figure 10). From 0% to 100% of crop area grazed is associated with a decrease in crop area by 206 ha and annual pasture area increases by 465 ha (Figure 10). The area of lucerne decreases by 205 ha accounting for the difference in the change in crop and annual pasture area. Supplementary feed costs increase by $15,542, (19%), from the 0% to 100% increase in crop paddock grazing. Overall farm profit falls by $85,247, (24%).

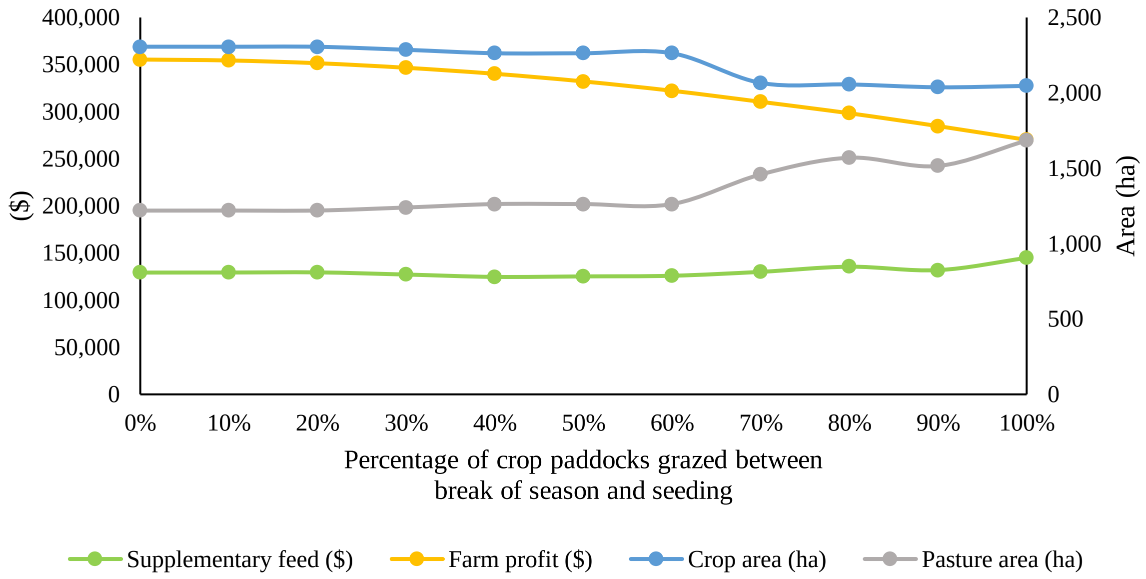

Figure 10. Impacts on farm profit, crop and pasture area and supplementary feed cost as the percentage of crop paddocks grazed between break of season and seeding increases on the predominantly heavy soils farm.

No access to glyphosate and paraquat restricts the ability to dry sow and as shown in Table 15, reduces farm profit by $14,332, (4%). Crop area decreases by 142 ha, pasture area falls by 24 ha, the area of lucerne increases and sheep numbers increase by 264 DSE causing an increase in emissions.

Table 15. Impacts on crop and annual pasture area, sheep numbers, emissions and farm profit for unconstrained dry seeding and no dry seeding of canola and lupins on the predominantly heavy soils farm.

	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
Dry seeding	2,306	1,219	12,280	3,270	355,348
No dry seeding	2,164	1,195	12,544	3,330	341,016

Yield losses associated with delayed seeding, caused by farmers' inability to access glyphosate and paraquat, could lead some farmers to purchase an additional seeder to accelerate seeding. Modelling this circumstance reveals a subsequent decline in farm profit by $34,296, (10%) (Table 16). Crop area decreases by 65 ha, annual pasture area increases by 101 ha, lucerne area decreases by 166 ha and sheep numbers decrease by 121 DSE and thus, emissions decrease.

Table 16. Impacts on crop and annual pasture area, sheep numbers, emissions and farm profit when there is no dry seeding and an additional seeder is purchased, or an additional seeder and sprayer are purchased on the predominantly heavy soils farm.

	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Total emissions (t CO_2e)	Farm profit ($)
No dry seeding	2,164	1,195	12,544	3,330	341,016
Seeder	2,229	1,296	12,423	3,277	306,720
Seeder and sprayer	2,092	1,433	12,677	3,339	283,489

Where an additional sprayer is also purchased then the outcome is a decline in farm profit by $23,231, (7.6%). Crop area falls by 137 ha, annual pasture area increases by 137 ha, sheep numbers increase by 254 DSE and emissions increase (Table 16).

The persistence of summer weed populations can limit potential yields of the following crop and pasture phases. A sensitivity analysis of reducing maximum yields of crop and pasture phases by 2% increments was modelled (Figure 11). Farm profit decreases by

$86,081, (30%), from 0% to 10% yield reduction, but little change occurs in crop and annual pasture area.

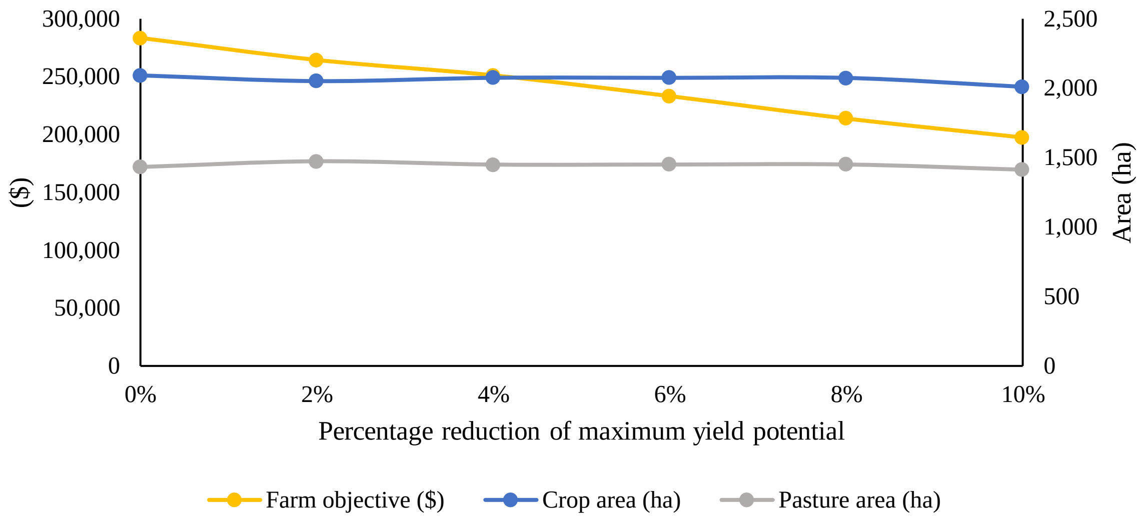

Figure 11. Impacts on farm profit, crop and annual pasture area, under a sensitivity analysis that reduces potential yields of crop and pasture phases by 2% increments on the predominantly heavy soils farm.

Table 17 summarises the cumulative impacts of the various management changes described above in response to the prohibited use of glyphosate and paraquat on the heavy land farm. Crop area percentage decreases from 66.7% to 53.6% over the range of analysed farm management changes and farm profit falls by $261,000. Land use change generally occurred on LMU 2, 4 & 6. Rotational choices for the base case, and the scenarios of no glyphosate and no glyphosate with HWSC are presented in the appendix. When these herbicides are no longer available and alternative weed control measures and farming system adjustments are required, then the main impact is a large decline in farm profit and a slight shift away from cropping into more sheep production. The decline in profit is caused by increased expenditure on weed control via the purchase of new machinery (e.g. HWSC or an extra seeder or sprayer), increased outlays on herbicides; and by reduced crop and pasture yields.

Table 17. Summary table of the impacts of the loss of glyphosate and paraquat on farm profit, crop area (as a percentage of the whole farm), herbicide costs, fertiliser costs, sheep number, LMUs on which land use change occurred and emissions on the predominantly heavy soils farm.

	Farm profit ($'000)	Crop %	Herbicide cost ($'000)	Fertiliser cost ($'000)	Sheep in May ('000)	LMU land use change	Emissions (t CO2e)
Base case with glyphosate & paraquat	458	66.7	186	240	11,914		3,216
No glyphosate	438	61.5	201	224	12,280	6 & 7	3,290
No glyphosate + HWSC	404	61.5	201	224	12,280	No change	3,290
NGNP[1] + HWSC	355	61.5	241	224	12,280	2 & 3	3,270
NGNP[1] + HWSC + Extra N	314	59.9	233	253	12,388	2, 6 & 7	3,293
NGNP[1] + HWSC + no dry seeding	341	57.7	248	216	12,544	4 & 6	3,330
NGNP[1] + HWSC + dry seeding + Extra seeder	307	59.4	235	220	12,423	2 & 4	3,277
NGNP[1] + HWSC + dry seeding and seeder + Extra sprayer	283	54.1	221	213	12,677	2 & 6	3,339
NGNP[1] + HWSC + dry seeding and seeder + Extra sprayer + 10% yield decline	197	53.6	217	184	12,830	4 & 6	3,299

[1] NGNP=No glyphosate and no paraquat

Note: Change in time of sowing is not included as land use change.

5.4 Grain price changes

The preceding analyses all assumed that loss of access to glyphosate and paraquat in Australia would not alter the commodity prices received by the types of farms modelled. That assumption is reasonable if a ban on those herbicides either solely applied in Australia or in most countries that were not major exporters of farm commodities that Australia also produced. However, if the ban on glyphosate and paraquat was more widespread, then international prices of agricultural products, especially those dependent on these herbicides (e.g. GT corn, GT soybean) would alter. By illustration, Brookes *et al*. (2017)'s analysis of a global glyphosate ban suggested loss of glyphosate would cause global prices of all internationally traded crops to increase. Drawing on Brookes *et al*., a sensitivity analysis was conducted by increasing prices received for all grains by 10% increments.

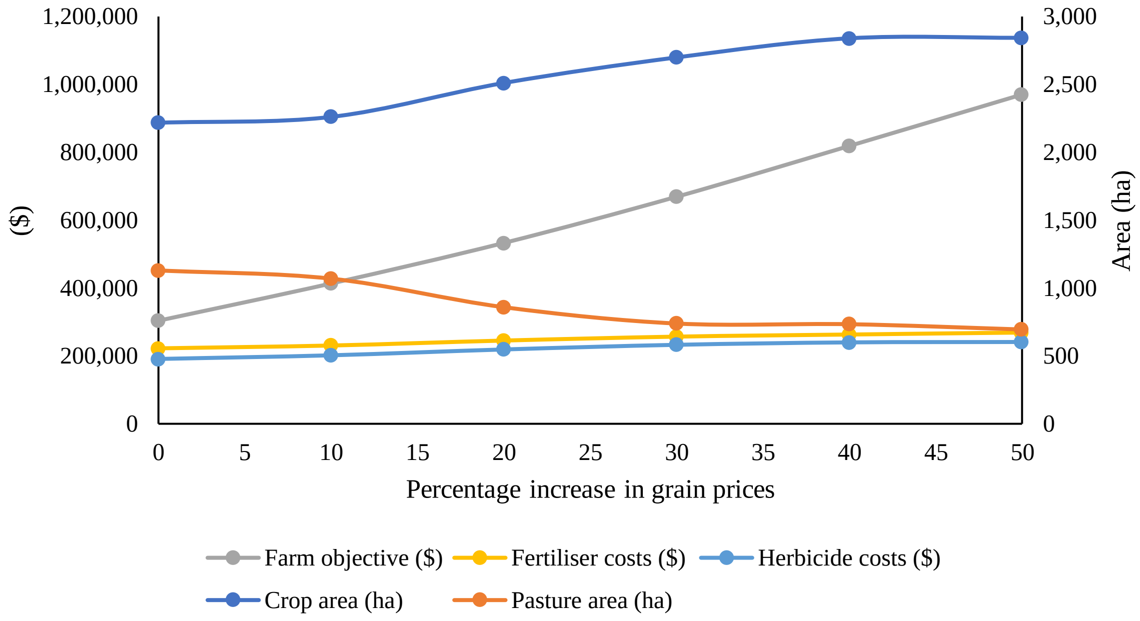

Figure 12. Impact on farm profit, crop and annual pasture area, herbicide costs and fertiliser costs when the prices received for wheat, barley, oats, lupins and canola increase for the average central wheatbelt soils farm.

The crop area increases as grain prices increase (Figure 12). Over the whole price range, the area of annual pasture decreases to 18% of the farm area. The costs of herbicides and fertilisers increase yet farm profit increases substantially. Over the whole range of grain price increases, farm profit increases by 219%, crop area increases by 28% and annual pasture area decreases by 38% with offsetting changes in the area of lucerne. Thus, despite all the required changes to accommodate the loss of glyphosate and paraquat as outlined previously in section 4.3, farm profit increases principally due to the magnitude of increases in the prices of grains.

The percentage increase in wheat, barley, oats, lupins and canola prices required for the farm’s profit to equate to pre-ban profits is only 11.5% (Table 18). Therefore, if a global ban on these herbicides was introduced, resulting in grain prices increasing, these prices would need to increase only by 11.5% for the profits on the average central wheatbelt farm to not be affected.

Table 18. Impacts of an 11.5% increase in wheat, barley, oat, lupin and canola prices for the average central wheatbelt farm when a ban on use of glyphosate and paraquat applies.

	Wheat price ($)	Barley price ($)	Oat Price ($)	Lupin price ($)	Canola price ($)	Crop area (ha)	Annual pasture area (ha)	Sheep in May (DSE)	Farm profit ($)
Base case (no ban)	295	295	235	305	540	2,261	1,069	12,364	429,787
11.5% increase in grain prices	329	329	262	340	602	2,248	1,069	12,364	429,787

6. Discussion

6.1. General comments

This thesis focuses on how loss of access to the herbicides, glyphosate and paraquat, might affect farms in the central wheatbelt of Western Australia. These herbicides principally underpin cropping activity. Hence, understanding where and why cropping occurs on these farms is crucial to exploring how loss of glyphosate and paraquat will affect the relative profitability of cropping and its place in these farming systems.

One of the strengths of the MIDAS model is its depiction of farm soil heterogeneity and how enterprise or rotation selection is influenced by the nature of the various soils. MIDAS usefully identifies which soils are especially suited to cropping, or solely suited to pasture production and which soils are jointly suited to cropping and pastures. For example, LMUs 6, 7 and 8 all produce good cereal and pasture growth. By contrast LMU 1 is a very poor sand more suited to low-cost pasture production rather than being committed to crop production that is often expensive relative to the returns generated. Loss of access to glyphosate and paraquat is more likely to be initially felt on soil types like LMUs 6, 7 and 8 where cropping is a main or highly preferred option.

The differences in the soil types and their proportions of a farm's area, for the range of farm types examined in this thesis, help explain why loss of access to glyphosate and paraquat affect these farms differently. The predominantly light land farm, for example, has the highest numbers of sheep and largest area of pasture. Hence, due to its lesser emphasis on cropping, loss of access to glyphosate and paraquat generates less dire impacts on this farm type compared to the other farm types.

Most farm management changes considered in MIDAS, in response to loss of the two herbicides, increase the input costs on crop hectares to a greater proportion than occurs on pasture hectares. This mostly results in the model's optimisation reducing the area of cropping and increasing the area of pasture and sheep numbers. However, as sheep are the main source of greenhouse gas emissions on these mixed enterprise farms, increases in sheep numbers generate increased emissions. Hence, one finding of this research is that removal of glyphosate and paraquat from farming systems, to address human health concerns, is likely to result in altered and less profitable farm systems that are slightly more polluting, inasmuch as greenhouse gas emissions increase.

On the average farm, when a ban on use of glyphosate and paraquat applies, most of the land use changes occur on LMUs 2, 7 and 8 that are sandplains, sandy surfaced valley clays and duplex soils. On the predominantly heavy soils farm, land use changes occur on LMUs 2, 4 and 6 which are sandplains, shallow duplex soils and heavy clays. On the predominantly light land farm, land use change typically occurs on LMUs 2, 5 (medium heavy soil) and 8.

Rotation changes typically occur on soils on which several different rotation options are similarly profitable. Often rotations are selected that have a lesser proportion of cropping phases thereby lessening the impacts of loss of glyphosate and paraquat. For example, on LMUs 7 and 8 are several rotations which offer similar levels of profitability. Hence, land use change occurs repeatedly on LMUs 7 and 8 across the three types of farms. However, there are rotation options on some soil classes that are so profitable that even though their profitability is reduced due to loss of access to the herbicides, and despite adopting management changes to restore farm profits, these rotations continue to be selected as part of optimal farm plans. In these situations, farm profits often are reduced despite little change in the farm's enterprise mix.

The efficacy of summer weed control affects the model outcomes; land use change, sheep numbers and farm profits, more than any other factor; other than the exogenous increases in grain prices caused by a widespread ban on use of these herbicides. The control of summer weeds, and the farming system implications of uncontrolled populations of these weeds demonstrates the importance of glyphosate and paraquat for summer weed control.

6.2 Critical review of results

The farming system implications of modelled impacts of management changes in response to loss of access to glyphosate and paraquat paint a sobering picture for the farm businesses modelled. Despite the several possible required changes in enterprise and farm management to minimise adverse impacts accompanying loss of these herbicides, nonetheless declines in farm profit, and in some cases large declines, are indicated as likely.

Of concern, there is no single inexpensive alternative weed control option to turn to once glyphosate and paraquat are no longer available. Discussions with farmers, advisers and weed scientists indicated a multi-faceted management response would be required, complicating the management of weeds in these mixed enterprise farming systems; and yet offering no likelihood of improved profits or even profit maintenance.

Moreover, one interesting finding of the analyses is the relatively small changes observed in land use, despite the magnitude of some of the reductions in farm profit. This indicates that on some land management units, the selection of particular rotations is very robust, implying farmers have few highly profitable alternatives to the currently selected land use. In some cases it also suggests that so pervasive across rotation alternatives is the use of glyphosate and paraquat that the relative profitability of many of these rotations is unaltered by a ban on use of these herbicides. A corollary of these impacts is that in many circumstances there is no attractive feasible option to substantially alter land use and thereby restore farm profit or at least reduce the decline in farm profit. Instead, farmers are likely to embrace a range of different tactics to better control weeds, but the outcome is primarily a reduction in farm profit.

A decrease in prices by 37.5% to 50% of the herbicides which replaced glyphosate and paraquat is unlikely to result from economies of scale as the production of these herbicides increase due to greater demand. There are, as well opposing price forces, increases in demand for a commodity places upwards pressure on price, therefore a price drop of this magnitude would not be expected.

The saying that adversity is the mother of invention may be applicable in these circumstances. The magnitude of the decline in profit exposes an opportunity for innovation. Avoiding losses can stimulate invention both at the farm and industry level. Development of new herbicides, new weed control technologies and novel management practices could be greatly encouraged, echoing the observation of Hayami and Ruttan (1985) who noted that economic conditions provide economic incentives for innovation.

There are some evolving weed control technologies not modelled in this study as they are currently not widely available or easily affordable. However, in time through additional research and development they could become commercially attractive; especially if a ban on use of glyphosate and paraquat applies. For example, site-specific spraying is a technology that when accommodated with green-on-green sensors allows weeds to be identified and individually sprayed in a crop as well as during a summer fallow. Site-specific spraying with green-on-green sensors can reduce chemical usage over summer by 94% (GRDC 2019). This technology would significantly reduce herbicide costs, a key consideration if glyphosate and paraquat are banned and need to be replaced by other more expensive herbicides. However, adoption of site-specific spraying with green-on-green sensors initially would involve a large capital investment in this novel technology.

Uncontrolled summer weeds were found to have the most significant adverse effect on farm profit when glyphosate and paraquat were not available, so in this situation there is a strong incentive to consider this technology, especially if the capital cost of this technology reduces in coming years. A related technology option is the ‘Weed Chipper’ that mechanically removes weeds identified with green-on-green sensors. This provides a weed control alternative which increases the sustainability of herbicides, through preventing the spread of herbicide resistant weeds (Walsh *et al*. 2020b). Machine-based learning for weed identification, better and cheaper cameras, improved dust protection and driverless technologies will only eventually enhance the commercial attractiveness of these methods of weed control.

Modelling results reveal that one of the strategic responses to loss of access to glyphosate and paraquat is often a slight shift away from cropping into sheep production, with the degree of the shift being dependent on the farm type and its existing suitability for cropping. Any enlargement of a farm’s sheep enterprise will increase labour demands on the farm family and its hired staff as the sheep enterprise is more labour intensive than cropping. However, already WA broadacre farms have issues of labour scarcity, and often farmers respond by opting to work more hours themselves (Rabobank 2007). Therefore, any changes in farming systems in the study region towards labour-intensive sheep production may be limited by labour scarcity in the study region or the inability to attract labour into the region.

Without glyphosate and paraquat, the spectrum of weeds will alter (Kudsk and Mathiassen 2020). Weeds will adapt to the new control methods, eventually lessening the effectiveness of these control methods. It is through this process of adaptation by weeds that Kudsk and Mathiassen (2020) suggest there will be ongoing negative economic consequences of a ban on these herbicides.

The crucial assumption most affecting farm profits that this study identifies is how widespread is the ban on glyphosate and paraquat. If the ban applies in Australia but not in other major grain-producing and exporting countries, then Australia will be especially disadvantaged. Under this scenario, world prices of traded grains would not greatly change as these prices are principally influenced by the volumes of GT crops grown in North and South America. The ramification would be that farm-gate prices received by farms in the study region would be largely unaffected.

However, if a global ban applied, then as outlined by Brookes *et al*. (2017), regions of the world dependent on production or purchase of GT crops (e.g. GT corn and GT soybean) would be especially disadvantaged. Regions such as Asia, India, and North and South America would be particularly disadvantaged and international grain prices would increase. Moreover, those increases in international grain prices only need to be of a moderate size (well under half what Brookes *et al.* estimate would occur under a global ban) for farms in the study region to be better off.

Furthermore, the mixed enterprise nature of the farm businesses in the study region enables these farms to advantageously respond to such relative price changes. Large increases in prices of any particular commodity (e.g. canola, wool or wheat) can trigger land use and management changes by farmers to embrace those market upsides.

In summary, there is no simple answer to the question: What are the Australian farm business impacts of loss of access to glyphosate and paraquat? The answer depends on several factors but most especially on how globally widespread is the ban on those herbicides. Currently, despite the legal cases brought before the courts in the USA, and despite decisions of some countries mostly in the European Union to ban use of those herbicides, it remains likely that North America and South America will continue to allow use of these herbicides, suggesting that a strong upward movement in grain prices is unlikely, as no global ban on these herbicides will apply. More likely is that an increasing number of countries, especially in the European Union, will ban use of these herbicides, thereby increasing costs of grain production in those countries, but that will only advantage other grain exporters like Australia still able to use those herbicides.

Given the importance of glyphosate and paraquat in underpinning the profitability of cropping systems in Australia it is unlikely that Australian governments would opt to ban glyphosate and paraquat, especially given statements from the APVMA (2017), Australia’s chemical regulator, about the safety of glyphosate. More likely is that some key markets for Australian grain could impose zero tolerance for any chemical residues of these herbicides in any imported grain, then Australian grain producers will either need to cease using these herbicides in order to guarantee access to those markets or accept potentially lower prices for greater volumes of grain sold in other markets still prepared to receive grain reliant on these herbicides. If farmers can no longer apply these herbicides, then they will be forced to adopt a range of more costly management tactics and strategies to control weeds. Eventually cost-effective technologies will become available to facilitate weed control, but that future remains several years away.

7. Conclusion

Glyphosate is an effective, cheap non-selective herbicide often used in combination with paraquat. This study examines the impacts of a ban on use of glyphosate and paraquat in Australian mixed enterprise broadacre farm businesses. We find the main determinant of these impacts is how globally widespread is the ban on use of these herbicides. The current indications are that an increasing number of countries, especially in the European Union, will ban use of those herbicides, thereby increasing the costs of grain production in the European Union, but that will only advantage other grain exporters like Australia still able to use those herbicides. If ever a global ban applied then, perhaps counter-intuitively, Australian farm businesses would likely benefit through higher grain prices on international markets generated by the inability to produce the major traded grains, GT corn and GT soybeans. However, a global ban currently seems highly unlikely. More plausible is where Australia opts to ban glyphosate and paraquat to ensure access to sizeable key markets that impose zero tolerance for any chemical residues of these herbicides in imported grain. Under such a circumstance, this study's analyses indicate that Australian grain producers would be greatly financially worse off.

Under the loss of glyphosate and paraquat, with no offsetting lift in grain prices, Australian broadacre farms modelled in this study reduce their area of cropping by between 10% and 13%, depending on the mix of soil types available to the farm business. The more crop dominant is the farming system then the greater is the decline in their farm profit due to the loss of glyphosate and paraquat. The most affected farms are those with a preponderance of clay and duplex soils suitable for cropping. Such a farm known as a heavy soils farm is shown to experience an annual profit decline from $458K down to $197K, due to raised weed control costs and crop yield declines due to less effective weed control.

Declines in farm profit occur for all types of farm businesses and farming systems considered in this study. This finding reveals that there are no management changes, or technologies immediately available to completely protect a farm business from the losses associated with a ban on use of these herbicides. Even the shift away from cropping into more livestock dominant farming systems does not remedy the impacts that flow from loss of glyphosate and paraquat. These herbicides so pervade land use that the relative profitability of rotation alternatives is mostly unaltered by a ban on use of these herbicides, negating substantial land use change as a means to restore farm profit or at least reduce the decline in farm profit. Instead, farmers are faced with the need to embrace a range of different tactics to better manage weed control, but the outcome is primarily a reduction in farm profit.

To lessen the reductions in farm profit, the modelling results in this study indicate that farm businesses will shift their production emphasis more towards sheep production. However, in turn this will unleash unfavourable environmental consequences. Greenhouse gas emissions from these farm businesses will increase. During a period of history when most nations are seeking to reduce their greenhouse gas emissions, one of the perhaps unforeseen implications of any ban on use of glyphosate and paraquat will be an increase in farm emissions via an enlargement of sheep flocks on affected mixed enterprise farms.

Any prolonged reduction in farm profit will eventually lessen the value of farmland. Hence, in the medium to long term, in the absence of cost-effective remedies, farmers face the sobering twin challenges of reduced incomes and ultimately reduced wealth through a lowering of the value of their farmland.

The magnitude of erosion of farm profits does provide a commercial opportunity for technology and practice innovation to restore profits. This study describes a couple of innovations in development that eventually may become commercially attractive. The likelihood is that cost-effective technologies will be developed to facilitate weed control, but that future remains several years away.

8. References

Australian Broadcasting Corporation (ABC). (2020). 'Bayer pays out $15.9b to settle Roundup cancer claims'. Australian Broadcasting Commission on-line report. Retrieved from: https://www.abc.net.au/news/rural/2020-06-25/bayer-to-settle-roundup-lawsuitswith-16n-payout/12389978

Australian Pesticides and Veterinary Medicines Authority (APVMA) (2017). Final regulatory position: Consideration of the evidence for a formal reconsideration of glyphosate. Retrieved from: www.dpmc.gov.au/pmc/publication/commonwealth-coat-arms-information-and-guidelines

Battaglin, W.A., Meyer, M.T., Kuivila, K.M. and Dietze, J.E. (2014). Glyphosate and Its degradation product AMPA occur frequently and widely in U.S. soils, surface water, groundwater, and precipitation, *Journal of the American Water Resources Association* 50, 275–290.

Beckie, H.J. (2006). Herbicide-resistant weeds: Management tactics and practices, *Weed Technology* 20, 793-814.

Beckie, H.J., Flower, K.C. and Ashworth, M.B. (2020). Farming without glyphosate? *Plants* 9: 96. DOI: 10.3390/plants9010096

Brookes, G., Taheripour, F. and Tyner, W.E. (2017). The contribution of glyphosate to agriculture and potential impact of restrictions on use at the global level, *GM Crops & Food* 8, 216-228.

Burnet, M.W.M., Hildebrand, O.B., Holtum, J.A.M. and Powles, S.B. (1991). Amitrole, Triazine, substituted Urea, and Metribuzin resistance in a biotype of rigid ryegrass (*Lolium rigidum*), *Weed Science* 39, 317–323.

Cameron, J. and Storrie, A. (2014). Summer fallow weed management in southern and western grains regions of Australia - a reference manual for grain growers and advisers. Grains Research and Development Corporation.

Chauhan, B. S., Gill, G. S. and Preston, C. (2006). Tillage system effects on weed ecology, herbicide activity and persistence: a review, *Australian Journal of Experimental Agriculture* 46, 1557-1570.

CSIRO and Bureau of Meteorology (CSIRO & BOM) (2018). State of the Climate 2018, CSIRO and the Bureau of Meteorology. Retrieved from: https://www.csiro.au/en/Showcase/state-of-the-climate

Deloitte Access Economics (2013). The economic impact of paraquat. A report prepared for Syngenta Australia Pty Ltd. Available at: https://www.syngenta.com.au/press-release/syngenta/deloitte-access-economics-estimates-18-billion-yield-loss-absence-paraquat

D'Emden, F., Llewellyn, R. and Burton, M. (2006). Adoption of conservation tillage in Australian cropping regions: An application of duration analysis, *Technological Forecasting and Social Change* 73, 630–647.

Department of Agriculture, Water and the Environment (DAWE) (2007). Agricultural Chemical Usage Database. Retrieved from: http://www.environment.gov.au/chmd_public/agriculturalDataSearch.do

Doole, G.J., Bathgate, A.D. and Robertson, M.J. (2009). Labour scarcity restricts the potential scale of grazed perennial plants in the Western Australian wheatbelt, *Animal Production Science* 49, 883–893.

Duke, S.O. (2012). Why have no new herbicide modes of action appeared in recent years? *Pest Management Science* 68, 505-512.

Duke, S.O. (2018). The history and current status of glyphosate, *Pest Management Science* 74, 1027–1034.

European Chemicals Agency (ECA) (2019). Glyphosate. Retrieved from: https://echa.europa.eu/hot-topics/glyphosate

European Food Safety Authority (EFSA) (2019). Glyphosate. Retrieved from: https://www.efsa.europa.eu/en/topics/topic/glyphosate

Farooq, M. and Siddique, K. H. M. (2015). Conservation agriculture: Concepts, brief history, and impacts on agricultural systems. In: Farooq M, Siddique K (eds) *Conservation Agriculture*, pp. 3–17. Springer, Cham.

Fletcher, A., Flohr, B. and Harris, F. (2020). Evolution of early sowing systems in Southern Australia. In: Pratley J, Kirkegaard, J (eds) *Australian Agriculture in 2020: From conservation to automation*, pp. 291–305. Agronomy Australia and Charles Sturt University, Wagga Wagga.

Fletcher, A., Lawes, R. and Weeks, C. (2016). Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop & Pasture Science* 67, 1268 -1280.

Gill, G. and Fleet, B. (2020). Integration of time of sowing, crop seed rate and herbicides for the control of annual ryegrass and brome grass. Grains Research and Development Corporation update papers.

Grains Research and Development Corporation (GRDC). (2018). Harvest weed seed control – beyond windrow burning. Retrieved from: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/harvest-weed-seed-control-beyond-windrow-burning.

Grains Research and Development Corporation (GRDC). (2019). Green on green camera spraying - a game changer on our doorstep? Retrieved from: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/green-on-green-camera-spraying-a-game-changer-on-our-doorstep3)

Harries, M., Flower, K.C., Scanlan, C.A., Rose, M.T. and Renton, M. (2020). Interactions between crop sequences, weed populations and herbicide use in Western Australian broadacre farms: findings of a six-year survey, *Crop and Pasture Science* 71, 491–505.

Haskins, B. and McMaster, C. (2012). Summer fallow management in 2010 across Central West NSW. Agronomy Australia.

Hayami, Y. and Ruttan, V. (1985). *Agricultural development : an international perspective (Revised and expanded)*. Johns Hopkins University Press.

International Agency for Research on Cancer (IARC) (2015). Evaluation of five organophosphate insecticides and herbicides, World Health Organisation. Geneva, Switzerland, IARC Monographs, vol. 112.

Jacobs, A. and Kingwell, R. (2016). The Harrington Seed Destructor: its role and value in farming systems facing the challenge of herbicide resistant weeds, *Agricultural Systems* 142, 33–40.

Jasieniuk, M., Brûlé-Babel, A. and Morrison, I. (1996). The evolution and genetics of herbicide resistance in weeds, *Weed Science Society of America* 44, 176–193.

Kanissery, R., Gairhe, B, Kadyampakeni, D., Batuman, O. and Alferez, F. (2019). Glyphosate: Its environmental persistence and impact on crop health and nutrition, *Plants* 8, 499. DOI:10.3390/plants8110499www.mdpi.com/journal/plants

Kim, J. W. and Kim, D. S. (2020). Paraquat: Toxicology and impacts of its ban on human health and agriculture, *Weed Science* 68, 208–213.

Kingwell R. S. and Pannell D. J. (1987). MIDAS, a bioeconomic model of a dryland farm system, Pudoc, Wageningen.

Kirkegaard, J. A. and Hunt, J. R. (2010). Increasing productivity by matching farming system management and genotype in water-limited environments, *Journal of Experimental Botany* 61, 4129–4143.

Kirkegaard, J. A., Conyers, M. K., Hunt, J. R., Kirkby, C. A., Watt, M. and Rebetzke, G. J. (2014). Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems, *Agriculture, Ecosystems and Environment* 187, 133–145.

Kniss, A. (2017). Long-term trends in the intensity and relative toxicity of herbicide use. Nature Communications 8, 14865 Available at: https://doi.org/10.1038/ncomms14865

Kudsk, P. and Mathiassen, S. K. (2020). Pesticide regulation in the European Union and the glyphosate controversy, *Weed Science* 68, 214–222.

Leon, M. E., Schinasi, L. H., Lebailly, P., Freeman, L. E. B., Nordby, K., Ferro, G., Monnereau, A., Brouwer, M., Tual, S., Baldi, I., Kjaerheim, K., Hofmann, J. N., Kristensen, P., Koutros, S., Straif, K., Kromhout, H. and Schüz, J. (2019). Pesticide use and risk of non-Hodgkin lymphoid malignancies in agricultural cohorts from France, Norway and the USA: a pooled analysis from the AGRICOH consortium, *International Journal of Epidemiology* 48, 1519–1535.

Llewellyn, R. S., Lindner, R. K., Pannell, D. J. and Powles, S. B. (2004). Grain grower perceptions and use of integrated weed management, *Australian Journal of Experimental Agriculture* 44, 993-1001.

Llewellyn, R., Ronning, D., Ouzman, J., Walker, S., Mayfield, A and Clarke, M. (2016). Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. Grains Research and Development Corporation.

Maggi, F., La Cecilia, D., Tang, F. H. M. and McBratney, A. (2020). The global environmental hazard of glyphosate use, *Science of the Total Environment* 717, 137-167.

Myers, J. P., Antoniou, M. N., Blumberg, B., Carroll, L., Colborn, T., Everett, L. G., Hansen, M., Landrigan, P. J., Lanphear, B. P., Mesnage, R., Vandenberg, L. N., Vom Saal, F. S., Welshons, W. V., Benbrook, C. M. (2016). Concerns over use of glyphosate-based herbicides and risks associated with exposures: A consensus statement, *Environmental Health* 15, 19. DOI: 10.1186/s12940-016-0117-0

Oerke, E.C. (2006). Crop losses to pests, *Journal of Agricultural Science* 144, 31–43.

Office of the Gene Technology Regulator (OGTR) (2003). Application for licence for intentional release of a GMO into the environment: Application No. DIR 020/2002. Department of Health.

Office of the Gene Technology Regulator (OGTR) (2020). Genetically modified (GM) crops in Australia: Fact Sheet. Available at: www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/9AA09BB4515EBAA2CA257D6B00155C53/$File/11%20-%20Genetically%20modified%20(GM)%20crops%20in%20Australia.pdf.

Padilla, J. T., and Selim, H. M. (2020). Chapter One - Environmental behavior of glyphosate in soils. In D. L. B. T.-A. in A. Sparks (Ed.), *Advances in Agronomy* (Vol. 159, pp. 1–

34). Academic Press. https://doi.org/https://doi.org/10.1016/bs.agron.2019.07.005

Pannell, D. Tille, P., Rodríguez-Cerezo, E., Ervin, D. and Frisvold, G. (2016). Herbicide Resistance: Economic and Environmental Challenges, AgBioForum 19, 136-155.

Pannell, D.J. and Gill, G.S. (1994). Mixtures of wild oats (Avena fatua) and ryegrass (Lolium rigidum) in wheat: competition and optimal economic control, *Crop Protection* 13, 371-375.

Pannell, D., Stewart, V., Bennett, A., Monjardino, M., Schmidt, C. and Powles, S. (2004). RIM: A bioeconomic model for integrated weed management of Lolium rigidum in Western Australia, *Agricultural Systems* 79, 305-325.

Powles, S. B., Lorraine-Colwill, D. F., Dellow, J. J., and Preston, C. (1998). Evolved Resistance to Glyphosate in Rigid Ryegrass (Lolium rigidum) in. In *Source: Weed Science* (Vol. 46, Issue 5). https://www.jstor.org/stable/4045968

Pratley, J., Baines, P., Eberbach, P., Incerti, M. and Broster, J. (1996). Glyphosate resistance in annual ryegrass. In Proceedings of the 11th Conference of the Grasslands Society of NSW. Available at: http://grasslandnsw.com.au/news/wp-content/uploads/2011/09/Pratley-Baines-Eberbach-Incerti-Broster-1996.pdf

Preston, C., Roush, R. and Powles, S. B. (1999). Herbicide resistance in weeds of southern Australia: why are we the worst in the world? Twelfth Australian Weeds Conference 454-459.

Rabobank. (2007). Positive outlook sees WA farmers most confident in the nation, though farm labour is an issue, results from Rabobank confidence survey, Rabobank Australia.

Rural and Regional Affairs and Transport Committee (2019). The independence of regulatory decisions made by the Australian Pesticides and Veterinary Authority (APVMA) Available at: https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Rural_and_Regional_Affairs_and_Transport/APVMA/Report [accessed Nov 14, 2020]

Stanton, R. A., Pratley, J. E., Hudson, D. and Dill, G. M. (2010). Herbicide tolerant canola systems and their impact on winter crop rotations, *Field Crops Research* 117, 161–166.

Tangamornsuksan, W., Lohitnavy, O., Sruamsiri, R., Chaiyakunapruk, N., Norman Scholfield, C., Reisfeld, B., Lohitnavy, M. (2019). Paraquat exposure and Parkinson's disease: A systematic review and meta-analysis. *Archives of Environmental and Occupational Health* 74, 225-238.

Thamo, T., Addai, D., Pannell, D.J., Robertson, M.J., Thomas, D.T. and Young, J.M. (2017). Climate change impacts and farm-level adaptation: Economic analysis of a mixed cropping–livestock system, *Agricultural Systems* 150, 99–108.

Tosun, J., Lelieveldt, H. and Wing, T. (2019). A case of ‘muddling through’? The politics of renewing glyphosate authorization in the European Union, *Sustainability* 11, 440.

Turner, N. C. (2011). More from Less – Improvements in Precipitation Use Efficiency in Western Australian Wheat Production. In *Rainfed Farming Systems* (pp. 777–790). Springer Netherlands. https://doi.org/10.1007/978-1-4020-9132-2_28

United States Environmental Protection Agency (USEPA) (2016). *Glyphosate Issue Paper: Evaluation of Carcinogenic Potential*. Retrieved May 30, 2020 from: https://www.epa.gov/sites/production/files/2016-09/documents/glyphosate_issue_paper_evaluation_of_carcincogenic_potential.pdf

Van Bruggen, A. H. C., He, M. M., Shin, K., Mai, V., Jeong, K. C., Finckh, M. R., and Morris, J. G. (2018). Environmental and health effects of the herbicide glyphosate. In *Science of the Total Environment* (Vols. 616–617, pp. 255–268). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2017.10.309

Walsh, M., Newman, P., and Powles, S. (2013). Targeting weed seeds in-crop: A new weed control paradigm for global agriculture, *Weed Technology*, *27*(3), 431–436. https://doi.org/10.1614/wt-d-12-00181.1

Walsh, M., Broster, J., Chauhan, B., Rebetzke, G., and Pratley, J. (2020a). Weed control in cropping systems – past lessons and future opportunities. In J. Pratley & J. Kirkegaard (Eds.), *Australian Agriculture in 2020: From conservation to automation* (pp. 151–172). Agronomy Australia and Charles Sturt University.

Walsh, M. J., Squires, C. C., Coleman, G. R. Y., Widderick, M. J., McKiernan, A. B., Chauhan, B. S., Peressini, C., and Guzzomi, A. L. (2020b). Tillage based, site-specific weed control for conservation cropping systems, *Weed Technology,* 1–7. https://doi.org/10.1017/wet.2020.34

Weed Science Organisation (2020). Current status of the International Herbicide-Resistant Weed Database. Retrieved from: http://www.weedscience.org/Home.aspx

Werth, J. A., Boucher, L. A., Thornby, D. A., Walker, S. B., and Charles, G. C. (2013). Changes in weed species since the introduction of glyphosate-resistant cotton, *Crop & Pasture Science*, *64*, 791–798. https://doi.org/10.1071/CP13167

World Health Organisation (WHO) (2010). The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification.

Young, M., Kingwell, R., Young, J. and Vercoe, P. (2020). An economic analysis of sheep flock structures for mixed enterprise Australian farm businesses, *Australian Journal of Agricultural and Resource Economics* 60, 1–23.

Zhang, L., Rana, I., Shaffer, R. M., Taioli, E., and Sheppard, L. (2019). Exposure to glyphosate-based herbicides and risk for non-Hodgkin lymphoma: A meta-analysis and supporting evidence, *Mutation Research-Reviews in Mutation Research*, *781*, 186–206.

9. Appendix - Key assumptions of farm modelling and more detailed results

Table A1. Farm gate prices for grains sold ($/t).

	Wheat APW 10%	Wheat GP1	Feed Wheat	Malt Barley 1	Malt Barley 2	Feed Barley	Oats	Lupins	non-GM Canola	GM canola	Field peas	Faba beans	Chick peas
Farm gate prices ($/t)	295	265	250	295	285	265	235	305	540	500	350	275	395

Table A2. Sheep sale prices in cents per kilogram of carcass weight by class and age of sheep when sold.

	Age (months)	Price (c/kg carcass weight)
Ewe Lambs	4	525
Ewe Hoggets	16	220
Ewes	64	180
Ewes	76	180
Wether Lambs	4	555
Wether Hoggets	16	270
Wether Hoggets	22	270
Older Wethers	>48	230

Table A3. Wool sale price in cents per kilogram, selling, testing and handling costs, and wool levy is based on the sale price of the wool.

	c/kg
Wool sale price	1575
Selling, testing & handling costs	28.5511
Wool levy	1.5%

Table A4. Herbicide options for each crop phase when glyphosate and paraquat are both available for use.

Crop phase	Herbicides applied	Total Cost ($/ha)
Lupins (wet sown)	Roundup CT Sprayseed 250 Simazine 900 Targa 200 Metribuzin 750 Select 240+adj. Paraquat 250 Brodal	68.47
Lupins (dry sown)	Simazine 900 Targa 200 Metribuzin 750 Select 240+adj. Paraquat 250	43.57
Field Peas	Roundup CT Sprayseed 250 Diuron 900 Select 240+adj. Broadstrike+adj. Metribuzin 750 Paraquat 250	68.14
Chick Peas	Roundup CT Sprayseed 250 Trifluralin 480 Simazine 900 Balance 750 Broadstrike+adj. Select 240+adj. Targa 200	102.20

	Paraquat 250	
Faba Beans	Roundup CT Sprayseed 250 Simazine 900 Metribuzin 750 Select 240+adj. Targa 200 Diuron 900 Paraquat 250	64.03
Wheat not after pasture	Roundup CT Sprayseed 250 Sakura 850 WG Diuron 900 Tigrex	78.63
Wheat after pasture[1]	Roundup CT Sprayseed 250 Sakura 850 WG Diuron 900 Tigrex Paraquat 250	89.15
Oats	Roundup CT Sprayseed 250 Diuron 900 Dual Gold MCPA LVE	40.14
Barley not after pasture	Roundup CT Sprayseed 250 Trifluralin 480 Tri-allate 500g/L Diuron 900	70.97

	Tigrex	
Barley after pasture[1]	Roundup CT Sprayseed 250 Trifluralin 480 Tri-allate 500g/L Diuron 900 Tigrex Paraquat 250	81.49
Lucerne establishment	Roundup CT Verdict 520+adj. Sprayseed 250 Trifluralin 480 Select 240+adj. Targa 200	78.31
Lucerne removal	Sprayseed 250	17.98
TT canola (wet sown) not after pasture	Roundup CT Sprayseed 250 Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj. Lontrel	71.13
TT canola (wet sown) after pasture	Roundup CT Sprayseed 250 Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj. Lontrel Paraquat 250	81.65

TT canola (dry sown)	Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj. Lontrel	65.77
GM canola not after past ('wet' sown)	Sprayseed 250 Roundup CT Roundup CT Trifluralin 480	62.39
GM canola (wet sown) after pasture	Sprayseed 250 Roundup CT Roundup CT Trifluralin 480 Paraquat 250	72.91
GM canola (dry sown)	Trifluralin 480 Roundup CT Roundup CT	47.12

[1] After pasture phases include the herbicide used to spray top the last year of pasture prior to the crop.

Note: Total per hectare costs of herbicides include application costs and the cost of adjuvants.

Table A5. Herbicide options for each crop phase when glyphosate is not available and paraquat is available for use.

Crop phase	Herbicides applied	Total Cost ($/ha)
Lupins (wet sown)	Pyresta Sprayseed 250 Simazine 900 Targa 200 Metribuzin 750 Select 240+adj. Paraquat 250 Brodal	53.85
Lupins (dry sown)	Simazine 900 Targa 200 Metribuzin 750 Select 240+adj. Paraquat 250	43.57
Field Peas	Paraquat 250 Sprayseed 250 Diuron 900 Select 240+adj. Broadstrike+adj. Metribuzin 750 Paraquat 250 Sprayseed 250	81.08
Chick Peas	Paraquat 250 Sprayseed 250 Trifluralin 480 Simazine 900 Balance 750 Broadstrike+adj. Select 240+adj.	113.29

	Targa 200	
	Sprayseed 250	
Faba Beans	Paraquat 250	73.79
	Sprayseed 250	
	Simazine 900	
	Metribuzin 750	
	Select 240+adj.	
	Targa 200	
	Diuron 900	
	Sprayseed 250	
Wheat not after pasture	Paraquat 250	91.57
	Sprayseed 250	
	Sakura 850 WG	
	Diuron 900	
	Tigrex	
	Sprayseed 250	
Wheat after pasture[1]	Paraquat 250	102.09
	Sprayseed 250	
	Sakura 850 WG	
	Diuron 900	
	Tigrex	
	Paraquat 250	
	Sprayseed 250	
Oats	Paraquat 250	53.08
	Sprayseed 250	
	Diuron 900	
	Dual Gold	
	MCPA LVE	
	Sprayseed 250	

Barley not after pasture	Paraquat 250 Sprayseed 250 Trifluralin 480 Tri-allate 500g/L Diuron 900 Tigrex Sprayseed 250	83.91
Barley after pasture[1]	Paraquat 250 Sprayseed 250 Trifluralin 480 Tri-allate 500g/L Diuron 900 Tigrex Paraquat 250 Sprayseed 250	94.42
Lucerne establishment	Paraquat 250 Verdict 520+adj. Sprayseed 250 Trifluralin 480 Select 240+adj. Targa 200 Sprayseed 250	91.98
Lucerne removal	Sprayseed 250	17.98
TT can (wet sown) not after pasture	Paraquat 250 Sprayseed 250 Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj.	84.07

	Lontrel Sprayseed 250	
TT can (wet sown) after pasture[1]	Paraquat 250 Sprayseed 250 Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj. Lontrel Sprayseed 250	87.47
TT canola (dry sown)	Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj. Lontrel Sprayseed 250	77.00

[1] After pasture phases include the herbicide used to spray top the last year of pasture prior to the crop.
Note: Total per hectare costs of herbicides include application costs and the cost of adjuvants.

Table A6. Herbicide options for each crop phase when glyphosate and paraquat are not available for use.

Crop phase	Herbicide applied	Total cost ($/ha)
Lupins (wet sown)	Basta Garlon Fallow Master Simazine 900 Targa 200 Metribuzin 750 Select 240+adj. Reglone Brodal	102.89
Lupins (dry sown)	Simazine 900 Targa 200 Metribuzin 750 Select 240+adj. Reglone	49.72
Field Peas	Basta Garlon Fallow Master Diuron 900 Select 240+adj. Broadstrike+adj. Metribuzin 750 Reglone	102.56
Chick Peas	Basta Garlon Fallow Master Trifluralin 480 Simazine 900 Balance 750 Broadstrike+adj. Select 240+adj. Targa 200	134.57

	Reglone	
Faba Beans	Basta	98.45
	Garlon Fallow Master	
	Simazine 900	
	Metribuzin 750	
	Select 240+adj.	
	Targa 200	
	Diuron 900	
	Reglone	
Wheat not after pasture	Basta	106.90
	Garlon Fallow Master	
	Sakura 850 WG	
	Diuron 900	
	Tigrex	
Wheat after pasture[1]	Basta	125.88
	Garlon Fallow Master	
	Sakura 850 WG	
	Diuron 900	
	Tigrex	
	Sharpen WG	
Oats	Basta	68.41
	Garlon Fallow Master	
	Diuron 900	
	Dual Gold	
	MCPA LVE	
Barley not after pasture	Basta	99.24
	Garlon Fallow Master	
	Trifluralin 480	
	Tri-allate 500g/L	

	Diuron 900 Tigrex	
Barley after pasture[1]	Basta Garlon Fallow Master Trifluralin 480 Tri-allate 500g/L Diuron 900 Tigrex Sharpen WG	118.22
Lucerne establishment	Basta Verdict 520+adj. Garlon Fallow Master Trifluralin 480 Select 240+adj. Targa 200	112.65
Lucerne removal	Basta	59.93
TT canola (wet sown) not after pasture[1]	Basta Garlon Fallow Master Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj. Lontrel	99.40
TT canola (wet sown) after pasture	Basta Garlon Fallow Master Atrazine Trifluralin 480 Atrazine+adj. Select 240+adj.	128.05

	Lontrel Reglone	
TT canola (dry sown)	Basta Garlon Fallow Master Atrazine+adj. Select 240+adj. Lontrel	100.62

[1] After pasture phases include the herbicide used to spray top the last year of pasture prior to the crop.

Note: Total per hectare costs of herbicides include application costs and the cost of adjuvant

Table A7. Rotation selection on each LMU of the base case scenario when glyphosate and paraquat are available on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	0	0	0	0	375	41	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	524	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	400
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	400	650	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	325
Total	260	400	650	400	375	375	565	725

Table A8. Rotation selection on each LMU where glyphosate is no longer available on the average central wheatbelt farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	0	0	0	0	375	84	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	481	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	419
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	400	650	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	306
Total	260	400	650	400	375	375	565	725

Table A9. Rotation selection on each LMU where glyphosate is no longer available and HWSC technology is applied on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	0	0	0	0	375	84	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	481	0
Canola, wheat, wheat, lupin	0	0	0	0	0	0	0	419
Wheat, canola (dry sown), wheat, lupin	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	400	650	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	306
Total	260	400	650	400	375	375	565	725

Table A10. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available and HWSC technology is applied on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	106	0	0	0	375	565	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	294	236	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	414	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	260	400	650	400	375	375	565	725

Table A11. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied and extra nitrogen fertiliser is applied on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	269	0	0	0	375	389	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	131	269	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	381	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
3 years pasture, canola, wheat	0	0	0	0	0	0	176	0
Total	260	400	650	400	375	375	565	725

Table A12. Rotation selection on each land management unit of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied and there is no dry sowing on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	103	0	0	0	375	108	0
Canola, wheat, wheat, lupin	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin	0	297	650	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	457	0
4 years lucerne, wheat, canola, barley, field pea, wheat	0	0	0	400	0	0	0	0
	260	400	650	400	375	375	565	725

Table A13. Rotation selection on each land management unit of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing and an extra seeder is purchased on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	268	0	0	0	375	286	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	279	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	132	269	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	381	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	260	400	650	400	375	375	565	725

Table A14. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing and an extra seeder and sprayer are purchased on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	400	0	0	0	375	345	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	220	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	0	295	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	355	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	260	400	650	400	375	375	565	725

Table A15. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing, an extra seeder and sprayer are purchased, and a 10% yield decline is applied on the average farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	260	400	0	0	0	375	285	0
3 years pasture, 1 year wheat	0	0	0	0	0	0	280	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	0	341	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	169	0	0	0	0
Wheat, canola, wheat, lupin	0	0	309	0	0	0	0	0
4 years lucerne, wheat, canola, barley (/), field pea, wheat	0	0	0	231	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	260	400	650	400	375	375	565	725

Table A16. Rotation selection on each LMU of the base case scenario where glyphosate and paraquat are available on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	97	0	0	332	95	280	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	52
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	488	840	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	43	0	0	678
Total	445	585	840	400	375	95	280	730

Table A17. Rotation selection on each LMU of the scenario where glyphosate is no longer available and HWSC technology is applied on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	101	0	0	333	95	280	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	51
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	484	840	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	42	0	0	679
Total	445	585	840	400	375	95	280	730

Table A18. Rotation selection on each LMU of the scenario where glyphosate is no longer available and HWSC technology is applied on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	101	0	0	333	95	280	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	51
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	484	840	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	42	0	0	679
Total	445	585	840	400	375	95	280	730

Table A19. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available and HWSC technology is applied on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	101	0	0	326	95	280	7
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	51
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin (dry sown)	0	484	485	0	0	0	0	0
Wheat, canola, wheat, lupin	0	0	355	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	49	0	0	672
Total	445	585	840	400	375	95	280	730

Table A20. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied and extra nitrogen fertiliser is applied on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	404	0	0	368	95	280	66
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	370
Wheat, canola, wheat, lupin (dry sown)	0	181	482	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	358	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	7	0	0	295
Total	445	585	840	400	375	95	280	730

Table A21. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied and there is no dry sowing on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	72	0	0	0	95	280	419
Canola, wheat, wheat, lupin	0	0	0	0	0	0	0	162
Wheat, canola, wheat, lupin	0	513	840	0	0	0	0	0
4 years lucerne, wheat, canola, barley (/), field pea, wheat	0	0	0	400	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	149
Total	445	585	840	400	375	95	280	730

Table A22. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing and an extra seeder is purchased on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	179	0	0	0	95	280	457
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	51
Wheat, canola, wheat, lupin (dry sown)	0	406	500	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	340	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	222
Total	445	585	840	400	375	95	280	730

Table A23. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing and an extra seeder and sprayer are purchased on the light-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	317	0	0	0	95	280	503
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	194
Wheat, canola, wheat, lupin (dry sown)	0	268	500	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	340	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	33
Total	445	585	840	400	375	95	280	730

Table A24. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing, an extra seeder and sprayer are purchased, and a 10% yield decline is applied on the light- soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	445	447	0	0	227	95	280	116
Canola, wheat, wheat, lupin (dry sown)	0	138	0	0	0	0	0	205
Wheat, canola, wheat, lupin (dry sown)	0	0	603	0	0	0	0	0
Wheat, canola, wheat, lupin	0	0	237	0	0	0	0	0
4 years lucerne, wheat, canola, barley (/), field pea, wheat	0	0	0	400	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	148	0	0	409
Total	445	585	840	400	375	95	280	730

Table A25. Rotation selection on each LMU of the base case scenario where glyphosate and paraquat are available on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	0	0	0	0	639	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	16	47	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	210	470	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
3 years pasture, canola, wheat, canola (dry sown), wheat, canola (dry sown), wheat	0	0	0	0	0	0	798	0
Total	70	210	470	400	375	655	845	725

Table A26. Rotation selection on each LMU of the base case scenario where glyphosate is no longer available for use on the predominantly heavy soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	0	0	0	0	639	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	16	47	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	210	470	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
3 years pasture, canola, wheat, canola (dry sown), wheat, canola (dry sown), wheat	0	0	0	0	0	0	798	0
Total	70	210	470	400	375	655	845	725

Table A27. Rotation selection on each LMU of the base case scenario where glyphosate is no longer available for use and HWSC technology is applied on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	0	0	0	0	96	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	559	845	0
Canola, wheat, wheat, lupin	0	0	0	0	0	0	0	725
Wheat, canola (dry sown), wheat, lupin	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	210	470	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725

Table A28. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available and HWSC technology is applied on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	0	0	0	0	96	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	559	845	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	210	109	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	361	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725

Table A29. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied and extra nitrogen fertiliser is applied on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	45	0	0	0	655	0	0
3 years pasture, canola, wheat	0	0	0	0	0	0	845	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	0	118	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	165	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	352	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725

Table A30. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied and there is no dry sowing on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	0	0	0	0	0	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	655	845	0
Canola, wheat, wheat, lupin	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin	0	210	470	26	0	0	0	0
4 years lucerne, wheat, canola, barley (/), field pea, wheat	0	0	0	374	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725

Table A31. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing and an extra seeder is purchased on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	101	0	0	0	0	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	655	845	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	109	129	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	341	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725

Table A32. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing and an extra seeder and sprayer are purchased on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	210	0	0	0	111	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	544	845	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	0	151	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	400	0	0	0	0
Wheat, canola, wheat, lupin	0	0	319	0	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725

Table A33. Rotation selection on each LMU of the scenario where glyphosate and paraquat are no longer available, HWSC technology is applied, there is dry sowing, an extra seeder and sprayer are purchased, and a 10% yield decline is applied on the heavy-soils farm.

	Land management units (LMUs)							
	1	2	3	4	5	6	7	8
Rotation	Area of each LMU devoted to the particular rotation (ha)							
Continuous pasture	70	210	0	0	0	33	0	0
3 years pasture, 1 year wheat	0	0	0	0	0	622	845	0
Canola, wheat, wheat, lupin (dry sown)	0	0	0	0	0	0	0	725
Wheat, canola, wheat, lupin (dry sown)	0	0	197	0	0	0	0	0
Wheat, canola (dry sown), wheat, lupin (dry sown)	0	0	0	171	0	0	0	0
Wheat, canola, wheat, lupin	0	0	273	0	0	0	0	0
4 years lucerne, wheat, canola, barley (/), field pea, wheat	0	0	0	229	0	0	0	0
3 years lucerne, wheat, barley	0	0	0	0	375	0	0	0
Total	70	210	470	400	375	655	845	725