Straw and living mulches compared with herbicide for under-vine weed control in a Public-Private Benefit Framework

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Abstract

A common practice in Australian vineyards is to manage under-vine weeds with approved herbicides applied one or more times each year. A current project is testing the potentials in a range of pasture species and cereal straw as under-vine mulches compared with herbicides for weed control. Grass and legume pasture species in under-vine trials in 2015-16 have shown promising results at some sites, with grape yields in some cases exceeding those of the herbicide control plots.

Weeds compete with vines for water and nutrients and may provide a 'green bridge' between seasons, hosting pests and pathogens below the vines. Among the problems with repeated use of herbicides is the evolution of resistant populations of weeds, and their spread within the vineyard and to neighbouring properties and public lands.

This study subtracts the costs of typical herbicide regimes and those of alternative mulches and other operational vineyard costs from the values of their respective grape yields, as baseline prices and yields vary over time, to define the distribution of Gross Margins for each treatment. Further subtracting the manager's living costs, annual overheads, interest and taxes for random 10-year samples of simulated yields and prices allows estimation of long-term distributions of decadal cash balances for each under-vine treatment. Showing the probabilities of vineyard financial viability, these are private financial risk profiles for each treatment, differing by location. Juxtaposing these with the value of reduced risk of herbicide-resistant weed seed spreading beyond the vineyard permits analysis in a Public-Private Benefit Framework.

1.0 Introduction

a. This study is aimed to evaluate the economic viability of mulches as alternatives to continuous spraying of under-vine weeds. Under-vine weed control with herbicide is relatively simple, effective, inexpensive and very widely used. However, it is known that repeated use of the same herbicide over many years has the effect of selecting for herbicide-resistant genetics in the weed population.

b. 2017 holds the distinction of being the 60th anniversary of the world's first scientific documentation of herbicide resistant weeds. In 1957 a spreading dayflower (*Commelina diffusa*) growing in Hawaiian sugarcane was found to be resistant to a synthetic auxin herbicide (2,4-D). On an Ontario (Canada) roadside in the same year, wild carrot (*Daucus carota*) was confirmed resistant to the same herbicide (Collis, 2016). Since that time, 252 species of weeds have evolved resistance to 161 herbicides that span 23 of the 26 known herbicide sites of action (Heap, 2017).

c. Farmers will not "be able to spray their way out of resistance problems." While herbicides are a critical tool for large-scale weed management, it is essential "that we surround these herbicides with diverse weed control methods in order to preserve their usefulness … not sit back and wait for something better to come along." (Stanley Culpepper, quoted in Collis, 2016).

d. Resistance to "Roundup" (glyphosate) has been reported in rigid ryegrass (*Lolium rigidum*) growing with South Australian and Western Australian grapes since 1999 and 2003, respectively; as well as in South Africa (2001), France (2005) and Italy (2007) (Heap, 2017). Gains and Heap (2016) have compiled a long list of weeds with mutations that confer resistance to glyphosate. Many annual ryegrass populations have now evolved multiple herbicide resistance across Australia (Broster and Pratley, 2006).

e. Glyphosate is the herbicide most frequently reported to induce resistance in weeds growing in combination with grapes around the world, including Sumatran fleabane (France and Greece), hairy fleabane (Australia, South Africa and the US) and horseweed (Greece & US). At least 12 other herbicide resistant weeds in association with grape production have been reported (Heap, 2017).

f. One tactic found to mitigate development of glyphosate resistance in rigid ryegrass (*Lolium rigidum)* is to follow the glyphosate application in one to two weeks with a paraquat application for a "double-knockdown" effect on the weed. The modelling results of Neve *et al*., (2003) indicated the 'double knock' tactic should indefinitely delay the onset of glyphosate resistance in *Lolium rigidum.* These two non-selective herbicides have different modes of action; glyphosate is an 'EPSP synthase inhibitor' while paraquat is a 'PSI Electron Diverter' (Heap, 2017). Weersink *et al*. (2005) noted that this 'double knock' tactic is not as effective in controlling weeds other than *Lolium rigidum*; thus, there is a need to also consider the survival of these others under a 'double knock' regime, as well as issues of phytotoxicity (harm to the crop), movement of resistant weeds to or from the farm, and risk of the 'double knock' treatment failing to prevent glyphosate resistance.

g. Presently there is evidence of *Lolium rigidum* populations exhibiting multiple resistance to both 'double knock' herbicides (glyphosate and paraquat) growing in grape crops in South Africa (2003) and Western Australia (2013). In 2009, a hairy fleabane population growing in Californian grapes was reported to have multiple resistance to the same 'double knock' combination of herbicides; in NSW (Australian) grapes, hairy fleabane resistant to paraquat was reported in 2016 (Heap, 2017).

h. The known cause of the rising incidence of herbicide resistance is the repeated exposure of weeds to herbicides. This is a recipe for the evolution of weed populations resistant to particular chemicals. What seemed to have been a magic solution may not be considered as such for long. These points highlight the need to find integrated weed management strategies to offset risks of herbicide resistance (Pratley *et al*. 1998).

i. While herbicide manufacturers have limited incentives to invest in developing the next 'silver bullet' chemical (Powles and Gains, 2016), it is most prudent for rural industries to explore other means. The present study aims to evaluate live mulch options for weed control under vines from the grower's economic viewpoint and from the perspective of public interest.

j. Where herbicide resistance has occurred in no-till broadacre farming, an attractive option for some included growing perennial pastures in multi-year phases with cropping for cost effective weed control (Doole, 2008; D'Emden *et al.,* 2008; Mojardino *et al*., 2004; Pannell *et al*. 2016). Grape-growers presently depending mainly on herbicides in no-till under-vine management may be interested in such alternatives.

2.0 Alternative means of weed management

a. A field trial aimed at finding alternative means of under-vine weed control in Iowa vineyards is illustrated by Nonnecke (2009). Mulches, in the form of straw or densely-sown grass (creeping red fescue) suppress weed growth. Both the straw mulch and herbicide treatments in Iowa were effective at conserving water, but to a fault, as they can lead to waterlogging. Eight cover crop treatments were applied for 12 consecutive years on a medium textured soil in a vineyard near Robertson, South Africa (Fourie, 2011), combining pasture legume and grass species, Tricicale and faba bean straws and herbicide and reporting on fruit yields, quality and weed control efficacy. Mixed Triticale and Faba bean straw mulches gave higher grape yields than any of the other treatments.

b. Mechanised placement of straw mulch under vines can be effective, if clean round-baled straw can be sourced economically (Grocke, 2012). Of course weed seeds can be introduced with the straw.

c. Shallow cultivation under the vines can be used to partially control weeds (Sloan, 2010; Rinieri, 2011). A disadvantage of herbicides is that soil organic matter will also diminish with the regular removal of plants other than the grape vines in a vineyard where these others enhance soil characteristics favouring the vines (Fourie *et al*., 2007).

d. In some locations it is economically feasible to integrate controlled sheep grazing as part of vineyard weed and vine management (Shannon, 2011). Because sheep would be required in the vineyard only some parts of a year, sourcing them when needed can be an issue. Damage by the sheep at some vine growth stages can limit their use for weed control (Doran, 2007).

e. Where public nuisances or environmental dis-services such as herbicide-resistant weed seeds or spray-drift may emanate from vineyards, vineyard owners could be held liable. Where ecosystem "services generated within vineyard properties are public goods, it is likely that government-generated incentives, rather than market-based payments, will be necessary as growers will have little financial interest in maintaining such services" (Tompkins *et al*., 2012).

f. Holland (2016), however, has shown that large numbers of US farmers report benefits in using some practices required for accreditation in “organic” production though they have no intention of gaining organic certification due to the additional, restrictive and costly requirements for certification and the lack of secure rewards in terms of price premiums.

g. In regions where mulches can be demonstrated to clearly offer better options from the grape-grower’s economic viewpoint, we should expect early adoption without any other incentives. This paper should help identify and clarify the incentives influencing grape-growers with regard to their costs and benefits of adoption, as well as the associated public costs and benefits. The definition of environmental and other conditions that favour particular weed-control options will be clarified with the additional observations possible with ongoing field trials and laboratory work.

3.0 This study has three aims:

a. **The first aim** is to qualify the public consequences of switching from herbicide to mulch-controls for under-vine weeds. With careful use of a herbicide such as “Roundup”, by alternating its use with non-chemical controls such as mowing, cultivation and grazing, the rate of evolution of herbicide resistance will be reduced. However, multiple sprays year after year can result in rapid selection in favour of herbicide-resistant weed populations. Spray-drift damage to vines or vegetation on neighbouring properties may occur accidently. The extent of potential damages will depend on the nature and sensitivity to such risks on neighbouring private and public lands and water. Spread of resistant weed seed outside the vineyard can be expected when resistance appears in vineyard weeds. Weed seeds travel on the wind, in runoff water, on the wheels of vehicles, on the feet of people and sheep. There are also major OH&S concerns with some herbicides, such as paraquat. These in most cases are kept well in hand as label-directions and other regulatory controls are observed by farmers.

b. With the limited results we have from the trials so far, and information on longer-run weather and price variations, **the second aim** is to compare distributions of vineyard profitability specific to key grape production regions and varieties using the two methods of weed management. The private consequences of keeping the current practice of using herbicides for under-vine weed control or switch to a 'mulching' approach will depend on differences in vineyard cost, effects on vineyard fruit yield and quality and efficacy in weed control. These costs and benefits may vary with weather and prices from year to year. Further, some customers insist on organic products grown without modern technologies such as herbicides or chemical fertilisers, often raising the costs of production. Freedom from herbicide is key to certified organic production. Therefore, weed control in the under-vine area is a major challenge to growers wishing to embark on organic production systems.

c. **The third aim** is to juxtapose private benefits and costs with public benefits and costs of the options. Mentioned earlier is the need for care in herbicide applications to avoid spray drift to the neighbour's crops or to public lands. The 'win-win' result desired (and expected for some locations) is for positive net private and net public benefits from change. In the marketplace, premiums are often paid for products guaranteed to be 'clean and green'. Particularly important to the positive image of Australian agricultural exports is to maintain the verifiable reality of the claim of safety and wholesomeness.

4.0 Materials and methods

a. Economic consequences of changing weed management in a private vineyard will depend on the cost elements of the changes and the biological responses affecting crop yields and quality. Weather and product price variations also affect the outcomes. Field trial results are available for one year from two contrasting South Australian districts (Barossa Valley and Langhorne Creek). These are in established vineyards, each growing the predominant grape variety for their districts (Shiraz and Cabernet Sauvignon, respectively). The trials, first sown under vines in 2014, were unsuccessful due to dry conditions and poor seed set. They showed no grape yield differences and had to be re-sown in 2015 for the grape harvest in 2016 to provide our initial basis for calculating baseline estimates of (grape) yields under the different treatments.

b. Variety-specific weighted average prices and yield levels for the harvests in each season over the 2006-2016 period were found for each of the two districts in the '*2016 South Australian Winegrape Crush Survey*' (SAWCS) published by Wine Australia (2016). This allowed historical ranges of district-specific yield x price variations for combination with fixed and variable costs to estimate distributions of economic outcomes. We adopt the method developed by Hutchings (2013) and exemplified in Hutchings *et al*. (2016) and Nordblom *et al*. (2016) for practical calculation of farm financial risk profiles.

c. We combine the economic results with information on public benefits and costs in a Public-Private Benefit Framework, following Pannell (2008). An example of the basic logic of this form of presentation of policy choices is given in Nordblom *et al.* (2015). Also see Pannell (2017) for many further examples.

5.0 Data

a. For the moment, our measure of public benefits and costs is qualitative, and considers both ceasing or reducing regular use of herbicide spray regimes under the vines or continuing dependence on them as usual. It also considers reduced threats to neighbouring properties from the spread of seed of herbicide-resistant weeds and from spray-drift of herbicides.

b. Wine Australia's 'South Australian Wine Crush Survey' (SAWCS, 2016) provides a rich source of information on district and variety-specific prices and yields from past years. We use price and yield data only from the 2006 – 2016 period. Visual estimates of prices were taken for Barossa Shiraz grapes from the 2016 SAWCS chart on page 34, and for Langhorne Creek Cabernet Sauvigon (Lang Ck Cab Sav) grapes from the chart on page 62. The price data obtained this way were already expressed in terms of dollars per tonne ($/t). The same charts presented grape production in terms of district totals harvested (or crushed) each season. These summed to 54 and 60 thousand tonnes (kt) in 2016 for all grapes in the Barossa and Langhorne Creek districts respectively.

c. The Shiraz grapes comprised about 60% of the Barossa district harvest, or 32.5 kt of a total 54.4 kt of all varieties together (2016 SAWCS, pp 33-34). Cabernet Sauvignon grapes accounted for about 30%, or 18.3 kt of Langhorne Creek's total 60.1 kt harvest (2016 SAWCS, p 61). These proportions of the focus varieties were applied to the annual total harvests in the previous years divided by their 2016 vineyard areas in the two districts (6,869 hectares (ha) and 1,879 ha, respectively) to estimate yields in tonnes per hectare (t/ha), from pages 35 and 63 (2016 SAWCS) for Barossa and Langhorne Creek districts.

d. The above results are sufficient to capture ranges and correlations among yield and price variations over the most recent 11-year period to illustrate the form of analysis that is used in our risk analysis. We take the historical yield series to represent the baseline cases of production, which employ multiple herbicide sprays each year for under-vine weed control. See **Table 1** and **Figure 1** for the historical series of prices and yields, which are the basis for generating prices and yields for 240 seasons (**Figure 2**) that were stochastically simulated to exhibit the same statistical characteristics (means, standard deviations and correlations). The Gross Revenues (price x yields) simulated for the two locations (in $ thousands /ha) as shown in **Figure 2c** are plotted as probability distributions in **Figure 3**, which indicate median Gross Revenues of about $7,500/ha in both locations.

e. The field trial of alternatives to repeated herbicide applications were set up in four replicated random blocks in a semi-commercial Shiraz vineyard in the South Australian Barossa district and a commercial Cabernet Sauvignon vineyard in the Langhorne Creek district. The control treatment in 2015 was the continued use of herbicides, **(Option 1).** Alternative mulch treatments in the trial included a sown cocksfoot perennial grass (*Dactylis glomerata*, cv Kasbah) **(Option 2)**; a sown annual ryegrass mixed with annual Burr-Medic (*Medicago polymorpha*) **(Option 3);** and a Triticale straw mulch **(Option 4)**.

f. As of this writing we have the grape harvest yields only for 2016 from the replicated plots at the two locations. As is common, yields from measured plots were greater than averages of commercial vineyard yields in 2016 mentioned in **Table 1**; therefore, in **Table 2** we use the trial plot yields of the alternative treatments relative to the herbicide control plots as yield indices for adjusting respective district-level (t/ha) yields in our risk analyses. For the moment, we assume similar proportionate yield effects across seasons with poor and good growing conditions. Further, we assume fruit quality is constant across all treatments at a location in a given season and price per ton is the district average price in that season. Current laboratory tests and future trial harvests will provide the bases for greater confidence in appropriately adjusting these initial assumptions.

g. For the present study we used the 11-year sequences of prices and yields (**Table 1**) to generate a longer, 240-season sequence. These simulated seasons were generated in a process using the vector of means (i.e., for P1, P2, Y1, Y2 in Table 1) and a variance-covariance matrix, which was derived from the standard deviations and correlation matrix in Table 1 for our 11-year history of grape prices and yields. A 'Cholesky Decomposition' routine can be used to simulate multivariate series of jointly distributed random yield and price variates that share the statistical characteristics of the original data set (Nordblom, 1987, pp 66-69). Dr John D. Finlayson used the more stable **'eigen decomposition'** of the variance-covariance matrix, as explained in his technical footnote (below)[1], to generate the 240 sets of stochastic price and yield variates illustrated in **Figure 2a** and **b**. This

[1] We wanted to draw samples from a specified multivariate normal distribution. Our approach was to combine MonteCarlo techniques with an eigen decomposition of the variance-covariance matrix of selected data. The statistical package R provides a convenient platform to perform these calculations. Specifically: we used the function 'mvrnorm' from the library MASS (see https://cran.rproject.org/web/packages/MASS/MASS.pdf).

captures information from the 11-year historical series beyond their averages and standard deviations, allowing a more complete and balanced analysis of the prospects for the different options. The historical series (Table 1) are neither independent nor wholly random. For example, the reported fruit yields for the two districts in the historic series are strongly positively correlated (**r=0.68**); as they are less than 100 km apart they tend to face high-rainfall years and drought years together. Because they face similar global markets, their prices are also positively correlated (**r=0.33**). The Barossa Shiraz grape harvest yields and prices were negatively correlated (**r=-0.53**), as expected for many agricultural commodities. Unexpectedly, the Langhorne Creek prices and yields were positively correlated (**r=0.35**); this positive correlation is also reflected in our 240-season simulation sequence (Table1 and Figure 2).

h. Ranking each of the Gross Revenue arrays behind **Figure 2c**, from their lowest to highest values allows plotting them as cumulative distribution functions (**Figure 3**). Because the Barossa fruit yields were lower, and prices higher than those of Langhorne Creek in our analysis, their median Gross Revenues (price x yields) were nearly the same, at about $7,500/ha. This is a coincidence that helps us illustrate the importance of costs in determining the likelihoods of business profitability and survival.

i. To calculate Gross Margins per hectare, starting with the Gross Revenues ($/ha) we subtract Operational Costs per hectare (**Table 3**), comprised of fixed and variable elements. Fixed annual costs are for requirements that do not vary with grape yields. Also subtracted from gross revenues are the variable costs; those <u>that do vary</u> with yields, including extra harvesting costs, extra harvest labour, transport costs, and levies, calculated as $/t. These operational costs are quantified in Table 3 with approximate values (based on an anonymous 2016 budget from Griffith, NSW), which in reality, must differ from vineyard to vineyard.

6.0 Analysis

a. Gross Margins (before manager's living expenses, overheads, interest and taxes) were calculated by subtracting the appropriate Operational Costs ($/ha in Table 3) from both Barossa and Langhorne Creek Gross Revenues (**Figure 2c**) for each of the 240 simulated price and yield seasons in the two districts, as illustrated in **Figure 4**. Notice that in each season both the Gross Revenue and Operational Costs vary with fruit yield (t/ha), adjusted relative to the HERBICIDE treatment according to the under-vine treatment option indices in **Table 2**. As Gross Revenue also varies with fruit price ($/t), Gross Margins vary each season with both price and yield of that season. Our Operational Cost assumptions for the items comprising fixed and variable costs each season have some elements specific to each of the four under-vine weed management options, with the HERBICIDE treatment taken to have the lowest cost. Thus, in each simulated season, we have the following expression:

Gross Margin = Gross Revenue – Operational Costs (fixed and variable)

In this equation, only the fixed costs are assumed to hold constant while the remaining terms will vary from season to season as grape prices and yields change.

b. Four arrays of 240 annual Gross Margin values, representing the four under-vine options, were produced for each of the two districts. Each of the 240 rows in the combined eight arrays are considered to have equal probability.

c. Curves indicating the probability distributions of annual Gross Margin values per hectare below specific amounts are presented in **Figure 4** for each of the four under-vine options for each district. Gross Margin values are on the horizontal axes and cumulative probabilities on the vertical.

d. If our assumptions on costs, prices, yields are correct, and the results of a single season's field trials are adjusted for better and worse seasons, the Gross Margin curves for the HERBICIDE Option 1 in both districts are slightly exceeded or matched by both Option 3 (BURR MEDIC) and Option 4 (TRITICALE STRAW mulch). In the Barossa district the straw mulch slightly beats Option 3. In Langhorne Creek, this ranking is reversed. However, the differences among Options 1, 3 and 4 appear insignificant. The large shortfalls in Gross Margins associated with COCKSFOOT perennial grass, Option 2, are due chiefly to the lower fruit yields measured in the field trials (Table 2) and projected here to hold in relative terms across the varying seasons in both districts. In the case of Langhorne Creek the indication is that Option 2 could lead to negative Gross Margins five years in ten; and less than 2 years in ten in the Barossa vineyard. Whether this initial perspective is valid should be clarified with future harvests and laboratory research.

e. Most pronounced are the large differences between the districts in Gross Margins per hectare due to the higher costs in Langhorne Creek. These are associated with higher annual fixed costs assumed for water and other inputs supporting that district's greater average productivity (Table 3), and consistent with this, higher annual variable costs at harvest, than in the Barossa area.

f. The indication in **Figure 4**, representing a Shiraz vineyard in the Barossa district, with Option 1 (HERBICIDE) outcomes, is for the probability of positive Gross Margins greater than 93%, with a median probability of reaching $2,300/ha and a 20% chance of exceeding $4,000/ha. Of course these probability estimates will change with different input costs.

g. The Cabernet Sauvignon vineyard in Langhorne Creek (Figure 4) with Option 1 (HERBICIDE) may encounter negative Gross Margins with 20% probability. Its median Gross Margin is about $1,900/ha and there is a 20% chance of exceeding $3,300/ha. The same caveat regarding the effect of different input costs applies in this district as well as the other.

h. Farm financial risk profiles that show the long-term probabilities of farm business profits and losses were approached in two additional steps. First, samples of ten-season length were drawn randomly from our 240-season series of Gross Margins for the 8 under-vine options across both districts. Assuming a vineyard area of 50ha for each such ten-season sample, we subtracted an assumed manager's annual living allowance (drawings) of $80K, annual overhead payments of another $80K, then subtracting accumulating interest and taxes year by year to calculate a decadal ending cash flow balance. See **Figure 5** for three examples of such sample decades in the Barossa case with decadal results for each of the treatments. In a good decade (209) of weather and prices the farm may produce profits of $1.5M. In a poor decade of weather and prices (55) farm losses may exceed -$1.0M. Within the 240-season sequence of Gross Margins are 231 unique decades in the random draw process.

i. Many random draws of decades from the Barossa and Langhorne Creek Gross Margin series were made for the Decadal cash flow calculations for each under-vine option. The smooth distributions of the resulting decadal cash flow balances define **Long-Run Farm Financial Risk Profiles**. We considered results with annual overhead costs of $80K and $120K separately for each district to demonstrate the effects on profitability. See **Figure 6** for the Barossa results. After subtracting from annual Gross Margins the manager's living expenses, and annual overhead payments, interest and taxes for each decade and each under-vine option we define points on their longer-term distributions. Notice the COCKSFOOT option has less than a 20% chance of profits and greater than 80% chance of losses over a random decade with $80K annual overheads. The HERBICIDE treatment has better than 85% chance of profits, while the BURR MEDIC and STRAW mulches indicate better than 94% chances of profits. The latter shows only a 5% chance of maximum decadal cash flow balance of $2M.

j. All Barossa risk profiles shift far down in decadal cash margins with an increase in annual overhead costs from $80K to $120K. Only the best options exhibit greater than 30% chances of long-term profits (Figure 6).

k. Long-run Farm Financial Risk Profiles for Langhorne Creek are given in **Figure 7**. Assuming $80K in annual overheads, the HERBICIDE under-vine treatment would be profitable with just over 40% probability. In contrast the BURR MEDIC option appears profitable with about 60% probability. Increasing annual overhead costs to $120K would leave the BURR MEDIC option with only 25% probability of profitability.

l. In order to put the farm risk profiles in more familiar terms, as probabilities of average annual cash flow balances, these are assembled in **Table 4** for all under-vine treatments for both districts and with both annual overhead levels.

7.0 Discussion

a. The field trial results are provocative in suggesting there may be yield-improving benefits from some mulch treatments, and yield-reducing effects of one. When joined with economic information, interest in continuing the field and laboratory research in this area is considerable. While our initial results are encouraging there are several important questions requiring answers. Among these is the need to gain a fuller understanding of the efficacy of the under-vine management options in suppressing weeds together with appreciation of how to maintain that efficacy over subsequent seasons.

b. In order to understand the biological interactions affecting grape yields and quality in the various under-vine weed management options, soil microbial populations have also been monitored in the plots with sampling and DNA analysis. Differences were found in soil microbial populations among the under-vine mulch plots and herbicide-only plots. It is hypothesised that these different microbial populations are instrumental and even key in vine productivity and fruit quality. Allelopathic (antagonistic) relations are found among some species of plants, microbes and invertebrates, and symbiotic (beneficial) relations are found among others. It is too early to say with confidence that a lower-yielding treatment compensates with better quality fruit, though this could be an a priori hypothesis. These processes need to be better understood and are part of the larger study.

c. Weeds compete with vines for water and nutrients and may provide a 'green bridge', hosting pests and pathogens between seasons below the vines. Going forward, there is a need to ensure that such undesirable characteristics are not exhibited by mulch options meant to take the place of weeds.

d. Where herbicide resistance is not (yet) in evidence locally, the rise of herbicide resistance around the world implies the prudent course is to explore such options.

e. If there are private economic benefits from integrated weed management using different control measures over time to maintain the efficacy of herbicides, most of these benefits will go to vineyard owners, justifying research levies they pay.

f. Specific recommendations on plant species giving the best results from under-vine mulching are likely to differ among districts as weed populations, soils, climates, input costs and output prices differ. Weed suppression is a key.

g. At stake in the world marketplace is the fact that premiums are often paid for products guaranteed to be 'clean and green'. It is particularly important to the image of Australian agricultural exports to maintain the verifiable reality of the claim of taste, safety and wholesomeness.

8.0 Conclusions

a. There is no reason to expect the recent 11 years of weather and prices to persist in the future. Different future price and yield scenarios can be explored to examine the changes in vineyard economic outcomes. Implicit in our results is the expectation of no differences in grape quality among the under-vine treatments for a certain variety. If there are found to be systematic quality differences that affect grape values per tonne, these must be taken into account. Another improvement in our analysis will come with field trial results in further seasons to escape our simple assumption of yield indices relative to yields of the herbicide treatment in one season holding over past seasons. We should expect somewhat different relative yields between seasons.

b. It is reasonable to expect a continued rise in herbicide resistance in vineyard weeds, so it is prudent to search for more sustainable alternatives, such as mulches. Considerably reduced use of herbicides will be required in many cases in order to preserve their usefulness and efficacy. We may expect that some mulch options will be more effective and efficient than others in making reduced herbicide use easier and more economically attainable than in the past. The private economic benefits of integrated weed management, using different control measures over time, to maintain the usefulness of herbicides, will largely be reaped by grape-growers over time, justifying the research levies they pay. Where herbicide resistance is not (yet) in evidence, the rise of herbicide resistance implies the prudent course is to explore such options.

c. Specific recommendations on plant species giving the best results from under-vine mulching are likely to differ among districts with yield and quality differences, as weed populations, soils, climates, input costs and output prices differ.

d. At stake in the world marketplace is the fact that premiums are often paid for products guaranteed to be ‘clean and green’. It is particularly important to the image of Australian agricultural exports to maintain the verifiable reality of the claim of taste, safety and wholesomeness. Public Good claims for the present research project can include reduced herbicide use to sustain its usefulness in integrated weed management, improved ecosystem service from the soil in terms of fruit quality and/or yield, reflecting positively on the region as well as from its and reduced diesel use and CO_2 emissions from multiple herbicide applications.

e. The present research project has made a start with some provocative results showing some under-vine treatments (Triticale straw and Burr medic) associated with better fruit yields than the herbicide treatment. A single year's trial results form part of the larger picture, which must be tested further for reliability and efficacy. If their costs are not much higher than we have assumed **and** fruit quality is not reduced, **and** weeds are controlled, then such treatments could readily find roles in integrated weed management. This would describe the '**Good result'** in Figure 8, where the private grape-growers and both the local and wider publics feel the benefits, vindicating the research effort. The '**Dream result**' in Figure 8 is hoped for, of course, but not required to justify this research.

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Table 1. Selected historic series of prices and yields, 2006-16*, and the comparable statistical characteristics of a simulated series of correlated random variables for risk analysis that mimics the historical sequence.

	P1 Barossa Shiraz price ($K/t)	P2 Lang Ck Cab Sav price ($K/t)	Y1 Barossa Shiraz yield (t/ha)	Y2 Lang Ck Cab Sav yield (t/ha)
2006	1.16	0.85	6.96	11.07
2007	1.51	0.92	3.48	6.57
2008	1.74	0.99	5.84	9.94
2009	1.51	0.82	4.48	7.52
2010	1.34	0.66	5.30	7.52
2011	1.19	0.58	5.54	6.40
2012	1.51	0.77	4.54	7.87
2013	1.72	0.89	3.77	7.61
2014	1.83	0.77	3.83	7.87
2015	2.13	0.84	3.89	6.31
2016	2.20	0.78	4.77	9.86

	P1	**P2**	**Y1**	**Y2**	**Statistical characteristics of simulated series (n=240) **** P1	P2	Y1	Y2
Means	1.621	0.807	4.763	8.048	1.638	0.813	4.711	8.101
STDEV	0.326	0.111	1.011	1.498	0.356	0.118	1.104	1.595
Correlations:								
P1	**1**	0.330	-0.525	-0.001	**1**	0.285	-0.514	0.003
P2		**1**	-0.150	0.350		**1**	-0.209	0.276
Y1			**1**	0.678			**1**	0.690
Y2				**1**				**1**

* **Source:** Wine Australia (2016). *2016 South Australian Winegrape Crush Survey*.

** Simulation based on the above historical series by John Finlayson

Table 2. 2016 yield indices of alternative mulches relative to herbicide controls at two locations, Barossa and Langhorne Creek. **Source:** authors

	no mulch	**---sown living mulches ---**		**applied mulch**
Treatment:	**HERBICIDE** control	Perennial **COCKSFOOT** grass	Ryegrass mixed with **BURR MEDIC**	Triticale **STRAW** mulch
Field trial location				
Barossa yield index	**1**	**0.881**	**1.033**	**1.104**
Plot yield (t/ha)	8.82	7.77	9.11	9.74
Langhorne Creek yield index	**1**	**0.754**	**1.083**	**1.092**
Plot yield (t/ha)	19.95	15.05	21.61	21.79

Table 3. Annual Vineyard Operational Costs, fixed and variable, by location*

COST CATEGORIES:	ANNUAL FIXED COSTS		VARIABLE COSTS		
	Barossa Shiraz fixed costs ($/ha)	Lang Ck Cab Sav fixed costs ($/ha)		Barossa Shiraz variable costs ($/t/ha)	Lang Ck Cab Sav variable costs ($/t/ha)
Undervine weed control Options					
1. Under-vine herbicide sprays	75	80			
Living mulch estabished & maitained					
2. COCKSFOOT perennial grass	150	150			
3. Ryegrass & BURR MEDIC	120	120			
Straw mulch purchase & apply					
4. TRITICALE STRAW mulch	600	600			
OTHER COSTS					
Other spray application costs	300	400			
Cultivation, sowing for inter-row veg	200	200			
Slasher-mulcher for inter-row veg	250	250			
Pruning	300	300			
Fertilisers					
Spreadable	300	300			
Foliar	70	70			
In drip irrigation water	75	75			
Insecticides	35	35			
Fungicides	260	260			
Vineyard repairs and maintenance	400	400			
Electricity for pumping	150	250			
Irrigation water	150	300			
Land/lease payments	500	500			
Crop Insurance (4% of gross returns)	301	296			
Harvesting	300	300	+	30	30
Freight				15	15
Levies				10	10
Labour/wage ($25/hr, 40 hrs/ha) + (2 hrs/t)	1,000	1,000	+	50	50
Fixed annual costs except under-vine ($/ha)	**4,591**	**4,936**			
Variable costs, depend on fruit yield ($/t)				**105**	**105**

*** Source:** except for mulch costs, this table is based on an anonymous 2016 budget from Griffith, NSW, with adjustments by the corresponding author to reflect yield differences

Table 4. 10%, 50% and 90% probabilities for average annual cash balances less than or equal to calculated dollar amounts after interest, taxes, drawings and $80K or $120K in annual overhead costs with four under-vine treatments in Barossa and Langhorne Creek vineyards of 50ha. **Source:** authors

BAROSSA

	$80K overhead			
Probability	HERBICIDE	COCKSFOOT	BURR MEDIC	STRAW
10%	-$4,200	-$62,169	$8,777	$7,907
50%	$52,293	-$26,001	$76,020	$78,761
90%	$140,081	$12,665	$173,928	$183,324

	$120K overhead			
Probability	HERBICIDE	COCKSFOOT	BURR MEDIC	STRAW
10%	-$67,710	-$128,505	-$55,579	-$57,014
50%	-$27,678	-$92,120	-$15,270	-$13,065
90%	$18,439	-$56,374	$45,828	$54,074

LANGHORNE CREEK

	$80K overhead			
Probability	HERBICIDE	COCKSFOOT	BURR MEDIC	STRAW
10%	-$126,437	-$221,304	-$99,001	-$130,206
50%	-$7,922	-$131,526	$33,353	-$340
90%	$104,719	-$73,882	$185,933	$132,203

	$120 overhead			
Probability	HERBICIDE	COCKSFOOT	BURR MEDIC	STRAW
10%	-$193,285	-$288,151	-$165,848	-$197,053
50%	-$74,364	-$198,165	-$37,314	-$67,267
90%	$2,095	-$140,664	$68,629	$14,562

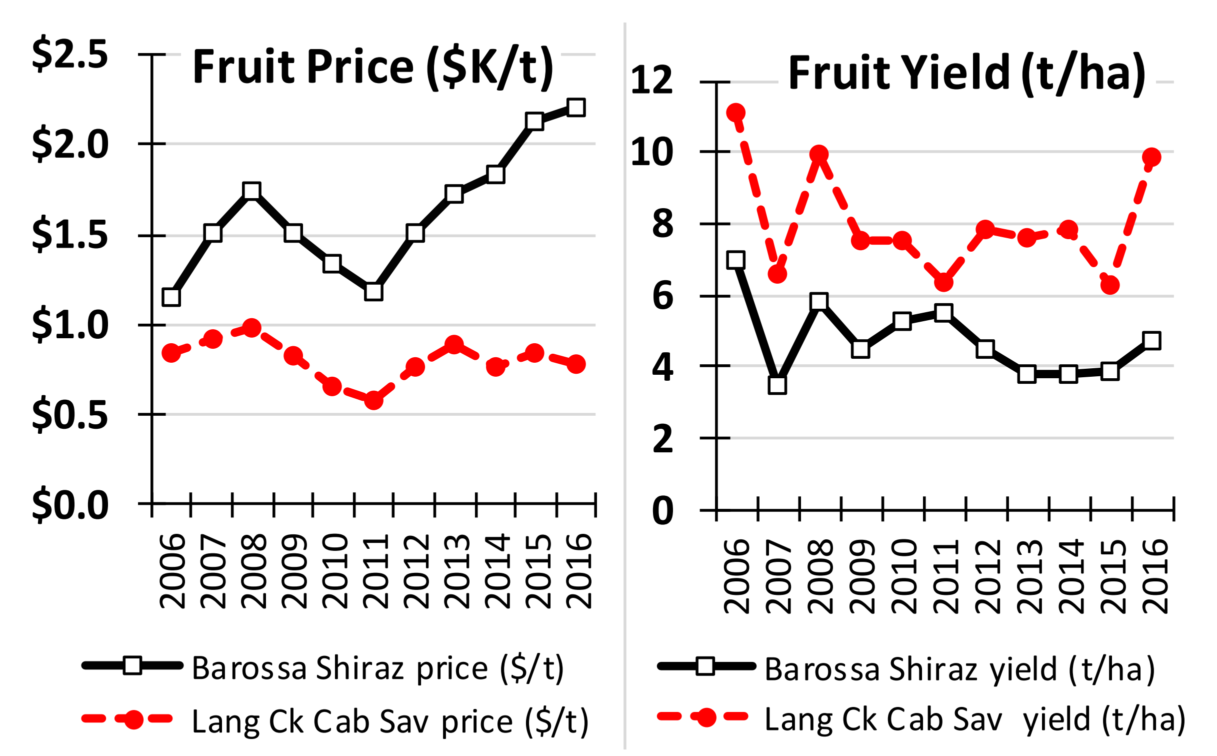

Figure 1. Reported fruit and price yields (2006-2016) for Shiraz grapes in the Barossa Valley and Cabernet Sauvignon grapes in the Langhorne Creek district.
Source: Wine Australia (2016) *South Australia Winegrape Crush Survey.*

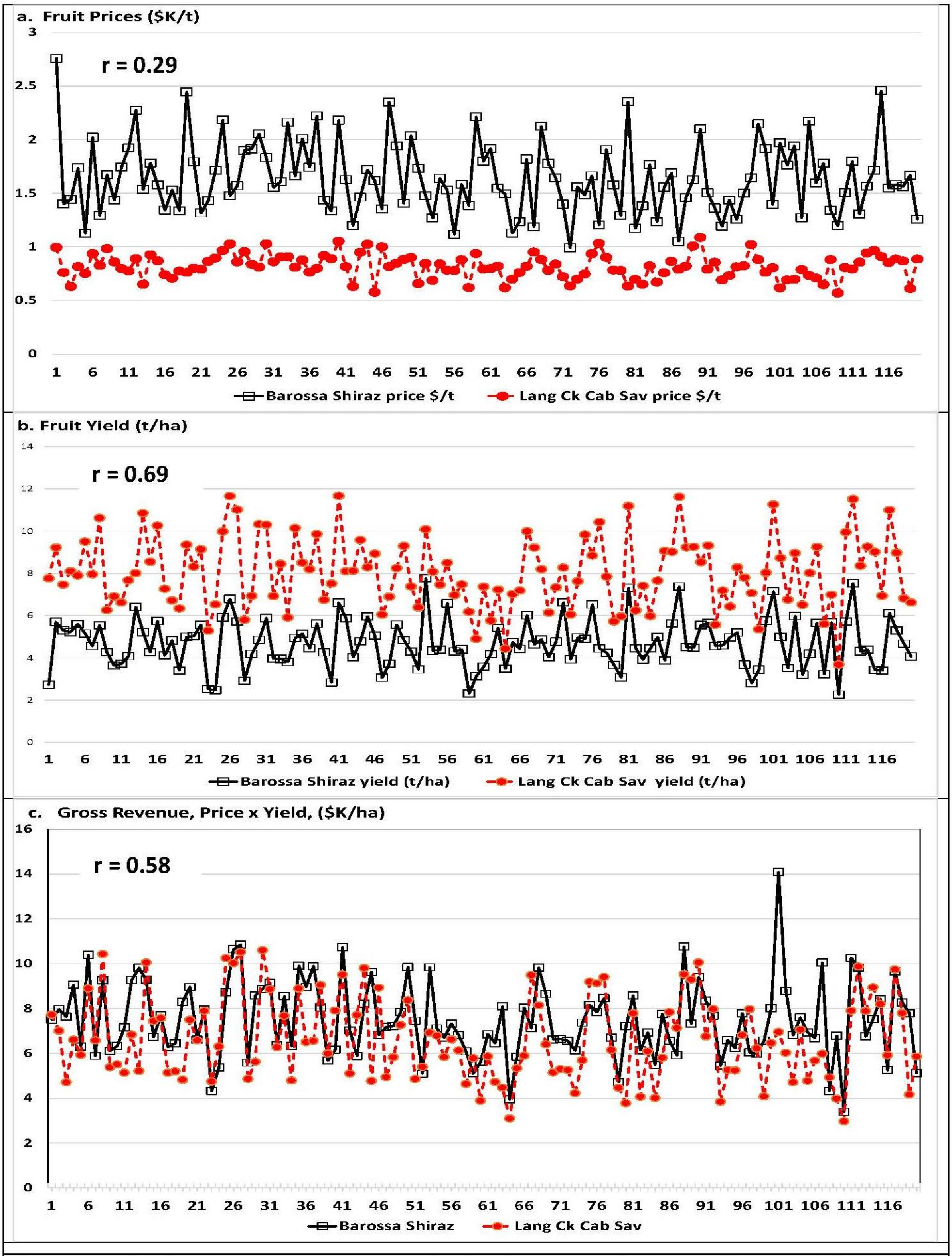

Figure 2. Simulated stochastic time series with correlated jointly-distributed random values for **a)** prices, **b)** yields and **c)** gross revenues of two variety / district combinations for 120 of 240 seasons with statistical properties modelled on 2006-2016. **Source:** derived from values in Table 1 by authors

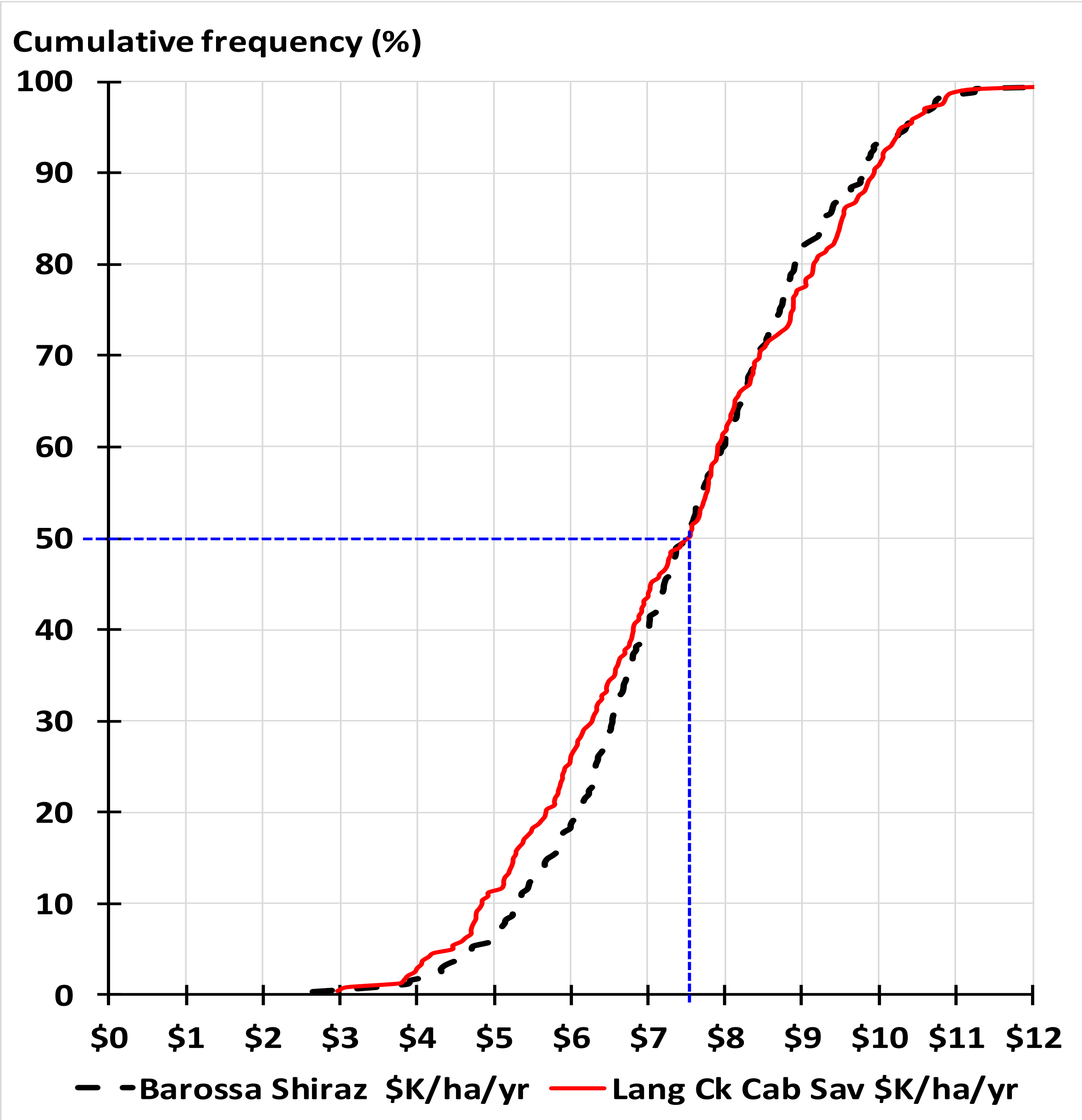

Figure 3. Annual gross revenues (price x yield) plotted as cumulative distribution functions based on simulated values as in Figure 2c.

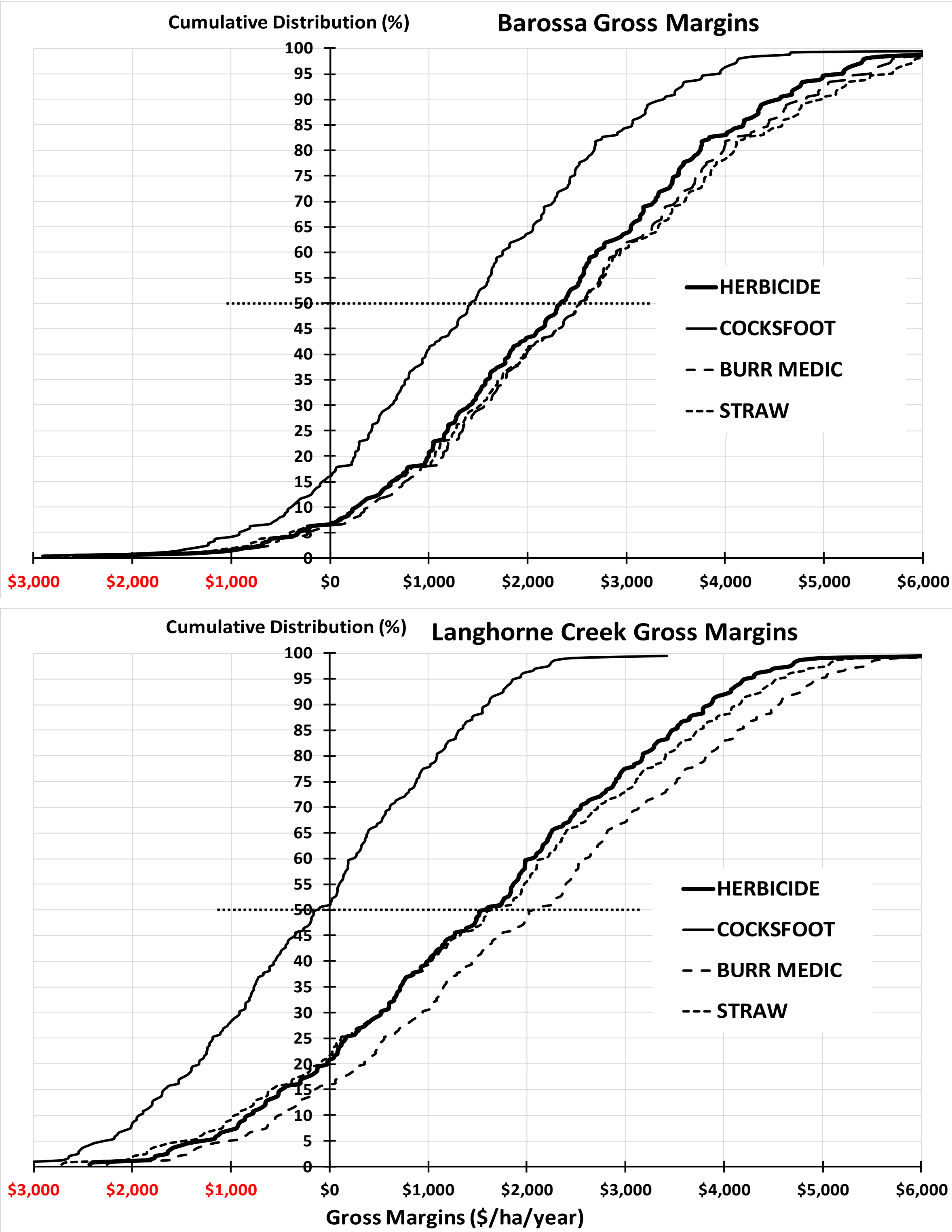

Figure 4. Cumulative distributions of Gross Margins: simulated as Gross Revenues minus Operational Costs ($/ha), before living costs, overheads, interest and taxes, of four under-vine treatments at experimental sites in two South Australian wine districts. **Source:** compiled by authors

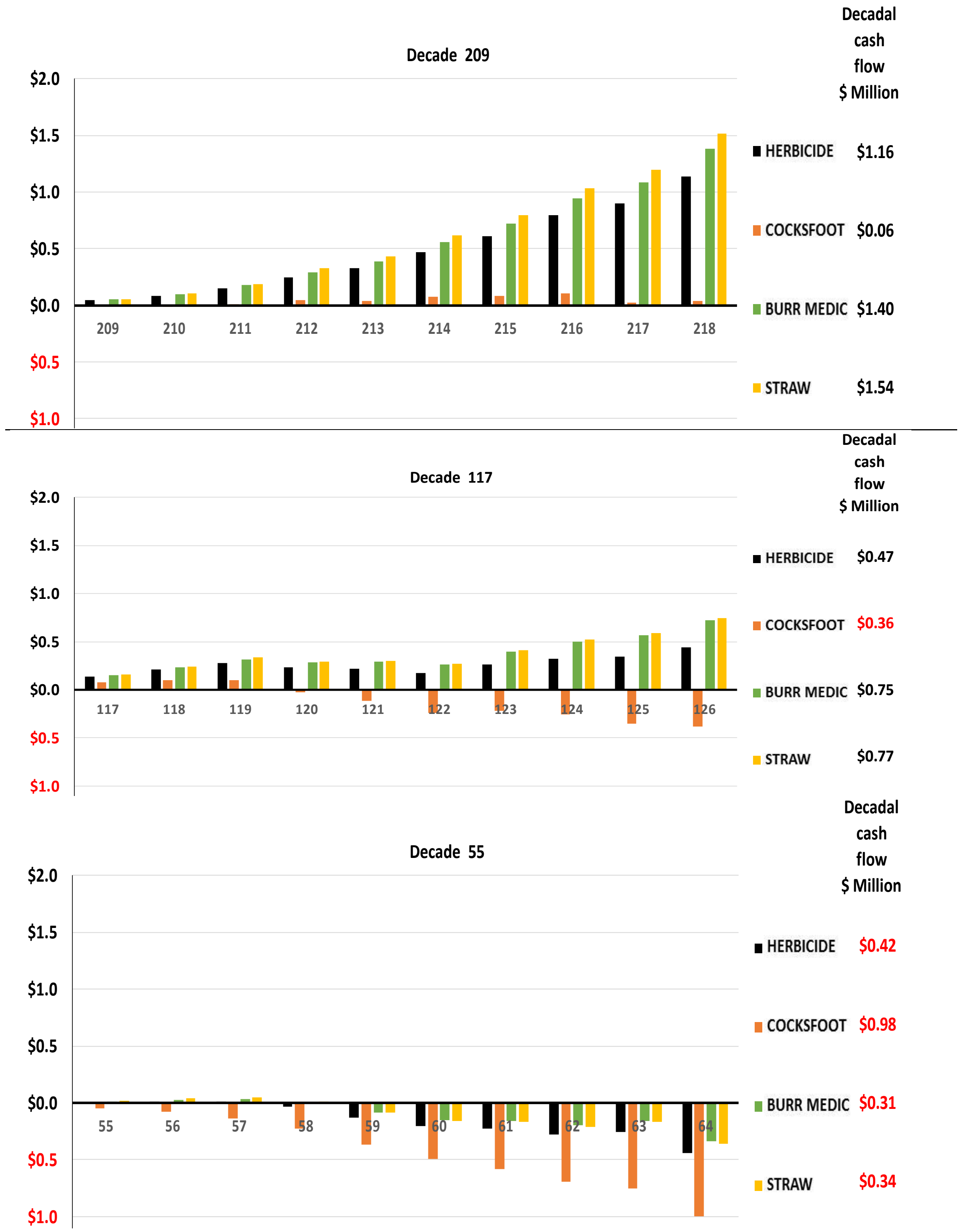

Figure 5. Examples of the annual and decadal cashflows (in $Millions) for a 50 ha Barossa vineyard with four under-vine treatments over three random decades (209, 117 and 55) among 231 stochastically simulated decades of varying fruit yields and prices, given $80K annual overhead costs. **Source:** compiled by authors

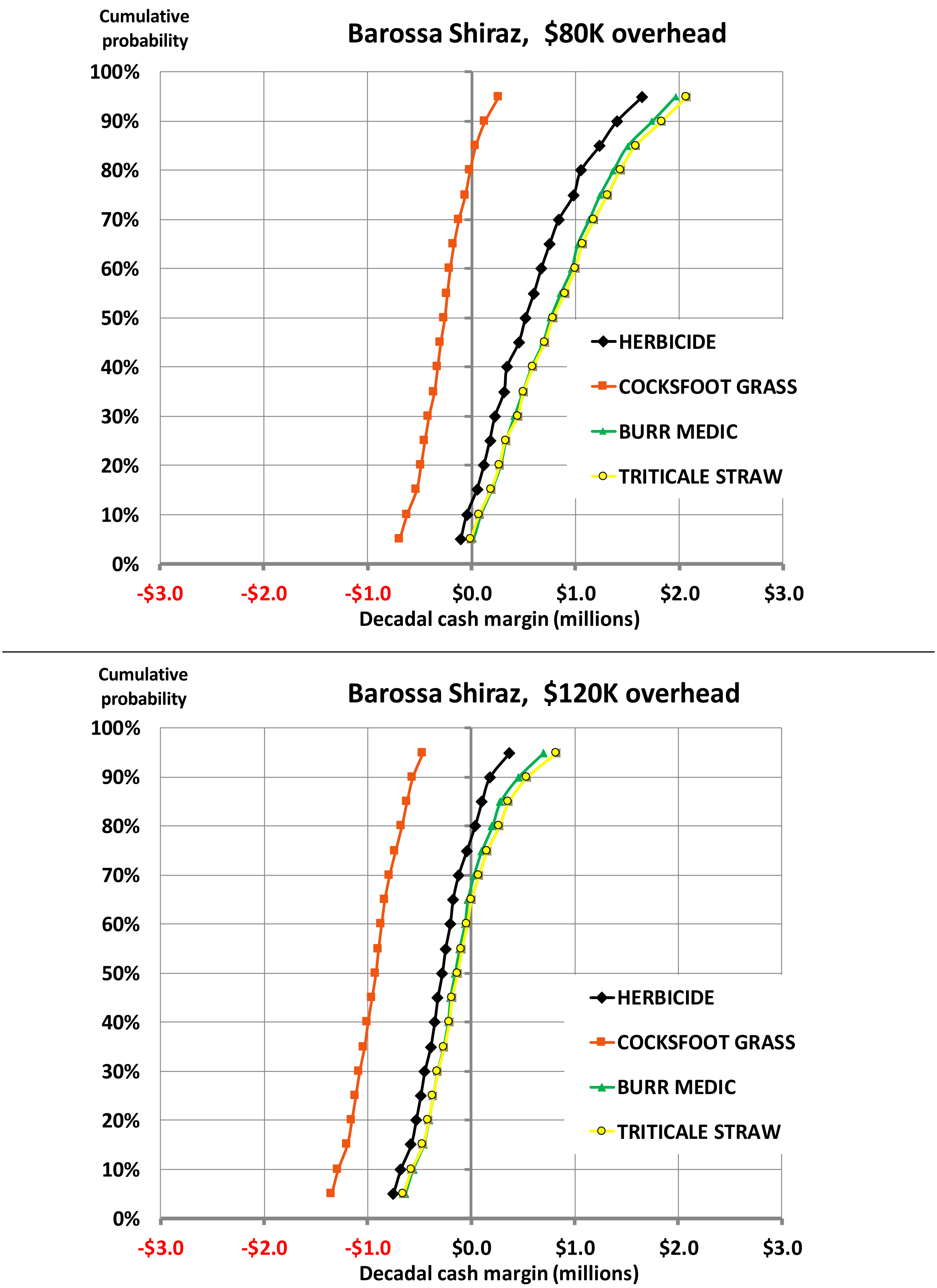

Figure 6. Cumulative distribution functions of decadal cash balance with four under-vine treatments on a 50 ha Barossa vineyard after interest, taxes, drawings and $80K and $120K annual overhead costs. **Source:** authors

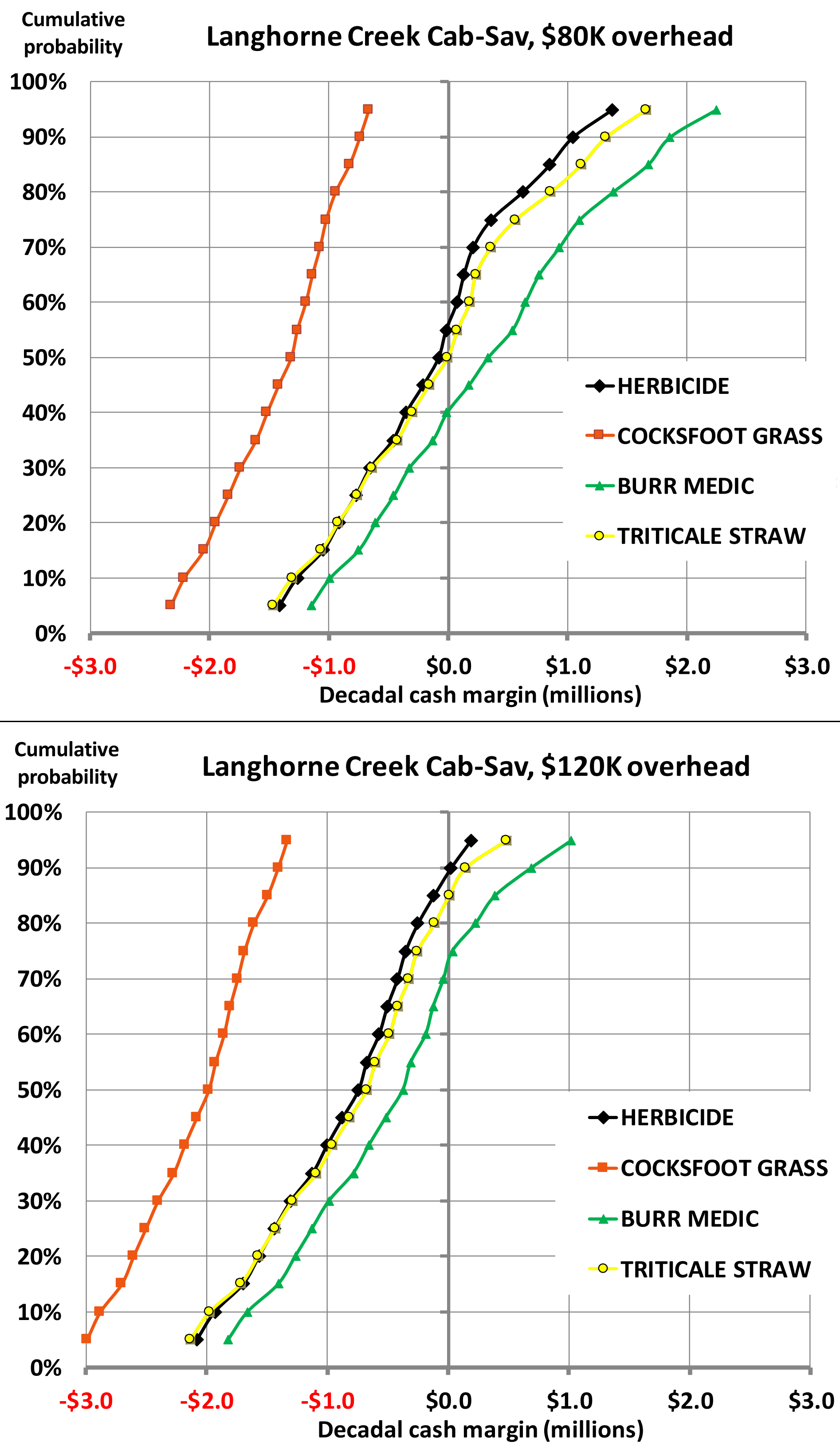

Figure 7. Cumulative distribution functions of decadal cash balance with four under-vine treatments in a 50 ha Langhorne Creek vineyard after interest, taxes, drawings and $80K and $120K annual overhead costs. **Source:** authors

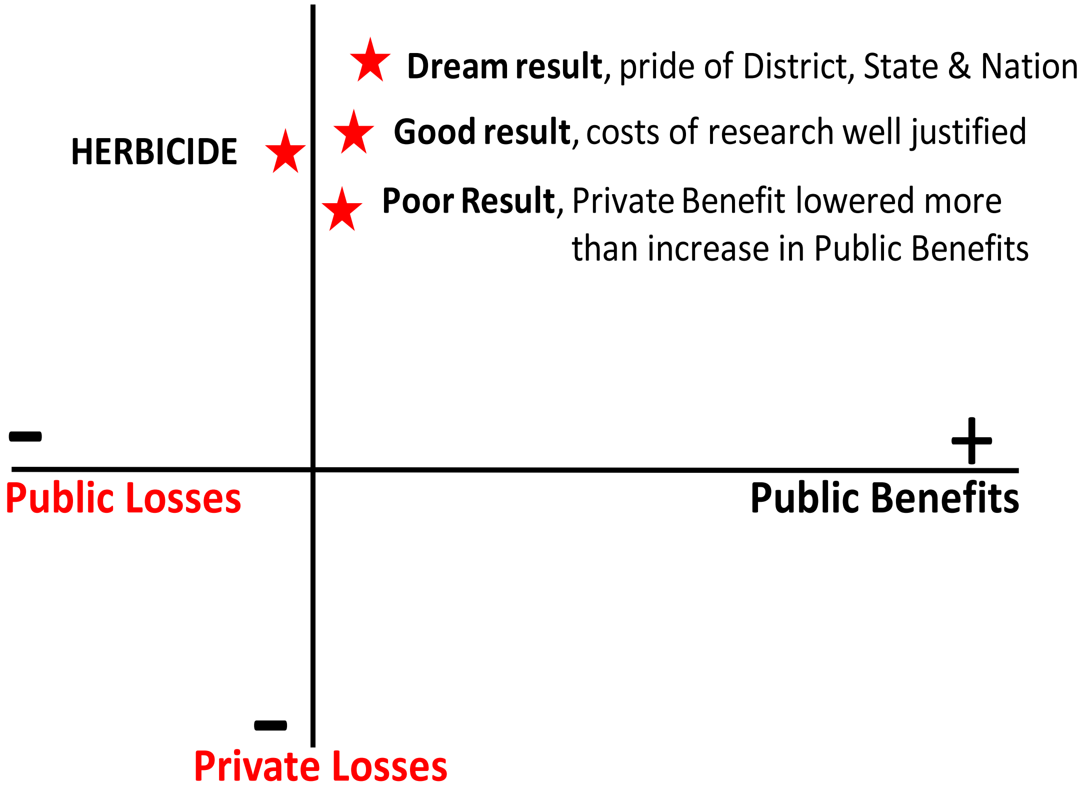

Figure 8. Research results in a public-private benefit framework (stylised). Presently, herbicides have important roles in vineyard weed management, being low-cost, easy to use and reliable. The rapid rise of herbicide resistance in weeds is a challenge to that reliability that will require integrating other means of weed management in vineyards as surely as it has in Australian broadacre agriculture. **Source:** authors