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Review

Tactical crop management for improved productivity in winter-dominant rainfall regions: a review

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Abstract. This study reviews published information on the tactical management decisions needed to maximise economic grain yield in winter-dominant rainfall regions of the Mediterranean type. Tactical decisions are defined as those relating to the period from immediately before sowing to harvest. Tactical management is the principal means by which farmers respond to changing environmental and short-term economic conditions as the season progresses. The review considers published evidence that underpins these decisions and relates to cereal crops (wheat, barley and oats), pulse crops (field pea, faba bean, chickpea and narrow-leaved lupin) and canola.

The criteria used to guide management decisions during the season involve soil and tissue tests for nutrients, knowledge of weed numbers and resistance status in the current and previous seasons, weather conditions that favour disease development, and knowledge of thresholds and biology of insect pests that may warrant control measures. All of these decisions can be related to the timing of the opening rains and the length of the growing season; the crop, pasture or weeds present in the previous two seasons; the presence of pest- and disease-bearing crop residues; and the type of tillage in use. Most of these indicators require further refinement through research across environments, soil types, crop types and production systems.

The likely interactions between tactical or short-term management decisions, longer term or strategic decisions, and genetic factors are discussed. The prevalent use of chemicals in the management of biotic factors that can impact the crops is noted, as is progress towards various systems of 'integrated' management of these threats to crop production. Most tactical decisions in rainfed cropping systems appear to be supported by adequate evidence, although some decisions are still based on practical experience and observations.

Application of tactical management practices together with strategic management and use of improved genotypes provides the possibility of achieving rainfall-limited potential grain yield at a regional scale. The papers reviewed have been selected partly on the basis that the experimental treatments achieved the estimated potential grain yield. Where the potential grain yields are not being achieved in commercial crops, it remains unclear whether this is due to inadequate adoption of existing information or inadequate research to identify and address the underlying causes. We highlight the need to devise a simple decision aid to assist farmers and their advisers to respond to the variable seasonal conditions evident since the turn of the Century.

Additional keywords: agronomy, canola, cereals, diseases, economics, insects, legumes, weeds.

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Introduction

Grain production in rainfed agriculture is inherently risky, largely owing to substantial variation in amount and distribution of annual rainfall (e.g. Australian Farm Institute 2012), leading to insecurity of the food supply in many regions (e.g. Amede and Tsegaye 2016). However, the grain produced from rainfed agriculture is important for world food supply, and the productivity of the farming systems in these areas needs to be improved to meet future world food requirements (e.g. Sadras and Angus 2006; Anderson 2010; Godfray *et al*. 2010), especially as the climate changes (Garrett *et al*. 2006; Ludwig *et al*. 2009; Luo and Kathuria 2013; Fischer *et al*. 2014). Grain yields (GYs) in rainfed agriculture can be improved in three broad areas: tactical, short-term or seasonal management (e.g. Turner 2004; Anderson *et al*. 2005); strategic or longer term management that largely involves soil improvement (e.g. Carter *et al*. 1998; Bakker *et al*. 2007); and genetic improvement (Fischer and Edmeades 2010). Analysis of the results of field experiments conducted over a range of rainfed environments tends to suggest that, after accounting for the effects of environment (site, location and season), the impact of management is at least twice that of genotype (Anderson 2010).

Tactical management practices based on field experimentation and observation and applied immediately before and during the growing season may involve adjustments to seeding rates (Leach *et al*. 1999; Tokatlidis 2014); variations in fertiliser rates (Jarvis and Bolland 1990; Robertson *et al*. 2012), placement (Nyborg and Hennig 1969) and timing (Anderson 1985; Seymour *et al*. 2016; Simpson *et al*. 2016); changes to sowing time and choice of maturity class of cultivars (Anderson *et al*. 1996; Stephens and Lyons 1998; Sharma *et al*. 2008) and to seeding depth and method (Schmidt and Belford 1993); dry sowing (Kearns and Umbers 2010); use of herbicide, disease and pest tolerant or resistant cultivars (Jayasena *et al*. 2018); and various chemical and non-chemical methods of weed management (Farooq *et al*. 2011; Walsh 2016; Moore and Moore 2020). Tactical management practices and their timing are not a fixed sequence but will vary according to seasonal and market conditions. The evidence discussed here comes largely from the winter-dominant rainfall areas in Australia that are Mediterranean-type environments, classified by Koppen–Geiger as Csa, Csb and BSk (Peel *et al*. 2007). These environments are found in the Mediterranean Basin and on the west coast of every continent at a latitude ~25–40° with an average annual rainfall of ~250–1000 mm.

Farmers in rainfed agricultural regions have also developed strategies that may need more than one season to take effect, but that can have an impact over many years in improving crop productivity. These strategies may involve practices such as fallow to conserve soil water (Guler and Karaca 1988); integration of animal production with cropping to diversify sources of income (Virgona *et al*. 2006; Schiere *et al*. 2006; Bell *et al*. 2014); use of legume or broadleaf crop rotations in conjunction with cereals to improve soil nitrogen (N) and assist disease and weed management (Donald 1962; Angus *et al*. 1991; Kingwell 1994; Doole and Weetman 2009; Christiansen *et al*. 2015; Renton *et al*. 2015); and various systems involving combinations of practices such as no tillage, retention of crop residues, deep ripping and application of gypsum to address soil compaction (Hamza and Anderson 2003), and controlled traffic farming and crop rotation to maintain soil fertility (e.g. Kingwell *et al*. 1993; Kingwell and Fuchsbichler 2011; Serraj and Siddique 2012; Loss *et al*. 2015; Alrijabo 2014; Sommer *et al*. 2014). There is some evidence that GY responses to tactical inputs and those obtained from strategic treatments such as soil improvements are additive (Anderson 2010). This paper concentrates on tactical management practices that can be used during the short-term, as previously defined.

Although the choice of crop cultivar cannot be changed after sowing, we view the choice of cultivar as a component of tactical management because the decision may change depending on the timing of the opening rains and the likely length of the growing season (Anderson *et al*. 1996). The use of cultivar mixtures (Fletcher *et al*. 2019) could be seen as an aspect of tactical management in reducing the risks of such factors as terminal drought and frost damage, anticipated disease risk (Loughman *et al*. 2000) or weed burden and resistance status. The differential response of crop cultivars to tactical agronomic inputs has not been widely confirmed but may be important under specific circumstances of environment and where differences between genotypes are large (Anderson *et al*. 2011).

Despite the difficulties of estimating and verifying the potential GY for rainfed crops (Anderson 2010), there is some evidence that the best farmers in the more favoured areas (fertile soils, more evenly distributed and reliable rainfall) and/or using the most advanced management can approach the estimated potential for common wheat (*Triticum aestivum* L.) (Poole *et al*. 2002; Abeledo *et al*. 2008; Richards *et al*. 2014; Robertson *et al*. 2012; Anderson *et al*. 2016). However, when regional average GYs are considered, the tendency is for GYs to approach the estimated potential only at seasonal rainfall ≤~250 mm (Anderson *et al*. 2005). This probably suggests that the management techniques associated with low seasonal rainfall are well accepted and dealt with by farmers, whereas the risks associated with the opportunities to increase GYs in the wetter seasons are unacceptably high, given the difficulty of predicting seasonal conditions. In either case, an estimate of the gap between average or actual GY and the estimated potential can be useful in deciding whether further effort to improve GYs is possible and likely to be profitable (e.g. Keating *et al*. 2003; Hochman *et al*. 2012).

In any given growing season, there is a sequence of decisions that are influenced by the likely GY or target GY, which is determined largely by the amount and timing of the seasonal rainfall. The timing of the opening rains sets the likely length of the growing season, the likely amount of rainfall, and thus the GY that is possible for a given set of soil physical and chemical conditions (Anderson 2010). Decisions regarding weed, pest and disease management during the season will be based on the likelihood of these factors reducing the target GY. The extent to which the target GY is realised will depend largely on the decisions made to manage and defend crop growth as the season develops. The whole-farm implications of various decisions have been examined further with respect to output responses (Kingwell 1994; Kingwell and Pannell 2005) and risk aversion (Kingwell 1997).

This paper summarises the published information available for making tactical management decisions and demonstrates how this information can be used to allow crop managers to approach more closely the target GY as set by the seasonal rainfall. Most of the published information considered in this review contains data that compare experimental GY with some estimate of the potential GY for each growing season. The information on tactical management, along with information on strategic management and improved genotypes, underpins the advice commonly given to farmers and, in addition, can supply functions in the construction of crop models.

Tactical agronomy

Start and length of the growing season

Most farmers have developed an experiential rule about the amount and timing of the opening rains constituting the start of the growing season. This rule commonly describes an amount in a single fall after a pre-determined date that may be based on the likelihood of frost damage resulting from early sowing. For example, 20 mm rain over 1–2 days after April 25 is a common criterion in some parts of the Western Australian (WA) grain belt. These ‘rules of thumb’ can likely be strengthened by further research. The end of the effective growing season can be estimated as the average temperature associated with grain maturity. For example, 23°C average maximum for wheat as used by French and Schultz (1984).

With these criteria, the length of each growing season for a given location, using local records, can be estimated and this length in turn can be related to the likely amount of seasonal rainfall each year (Anderson 2010). Thus, in a given season on the date when the opening rains are received, the likely length of the season and the likely amount of rain can be estimated for a given location.

Target grain yield

By using the estimated seasonal rainfall, a target GY can be estimated at the start of each season with either a simple water-balance equation (Nix and Fitzpatrick 1969; French and Schultz 1984; Anderson 1985) or a more sophisticated crop model using more variables that may influence crop growth and GY (e.g. Stephens *et al*. 1989; Keating *et al*. 2003). This target GY, however estimated, can be updated during the season according to the actual rainfall received, as distinct from the estimate at the beginning of the season. This may be one method of adapting to the changes in rainfall patterns that have been noted by Stephens *et al*. (1989) and reflected in average wheat GYs subsequently (ABARE 2017). It may also be used to vary the rates of fertilisers required to achieve the target GY.

Time of sowing and choice of cultivar

It is generally accepted that longer season (later maturing) wheat cultivars should be sown early in the season when the opening rains occur early, and shorter season (early maturing) cultivars can be sown later (e.g. Doyle and Marcellos 1974; Anderson *et al*. 1996; Stephens and Lyons 1998). Long-season wheat cultivars may yield the same as mid- or short-season types when sown later (Sharma *et al*. 2008); however, the grain quality (small grain screenings, hectolitre weight) of long-season cultivars may be unsatisfactory when sown later in the season (Sharma and Anderson 2004).

In addition to reducing exposure to drought and frost damage by matching cultivar maturity to anticipated length of growing season, seasonal financial risk can be reduced by choosing cultivars attracting a price premium. For example, hard, soft and high starch-quality wheat cultivars that may qualify for premiums can be grown with minimal risk if the rotation and soil type are appropriate, even if their GY potential is not high (Anderson and Sawkins 1997; Anderson *et al*. 1995, 1997).

Plant population or seed rate

The target GY can be used to estimate the plant population or seed rate needed to support that target. For example, a population of 40 wheat plants/m^2 is required in WA for each tonne of target GY (Anderson *et al*. 2004). However, given the benefits of increased plant numbers for weed management (Radford *et al*. 1980; Walsh and Minkey 2006) and the reduced crop establishment expected at higher seed rates (Del Cima *et al*. 2004), the seeding rates required for various GYs of wheat, for example, can be estimated as in Table 1. It can be hypothesised that if a seed rate of <100 kg/ha is used for a target GY of wheat of 4 t/ha, then plant numbers could be the factor that limits GY in a given season. In addition, information from the current and previous seasons about the likely weed burden can be used to adjust the seeding rate.

This type of relationship also appears to apply to narrow-leaved lupin (*Lupinus angustifolius* L.) in WA (French *et al*. 1994) and canola (*Brassica napus* L.) (Seymour 2011; French *et al*. 2016; Roques and Berry 2016). This requires further testing for a range of crop species relevant to the rainfed agricultural regions because similar relationships may not hold in other crops (Jettner *et al*. 1998). In all cases, the germination percentage and average size of the seed to be sown should be factored into the seed-rate decision (e.g. French *et al*. 1994).

Determination of fertiliser type and amount

For nutrients such as phosphorus (P), potassium (K) and sulfur (S), soil tests taken before seeding are reliable indicators of deficiency for plant growth and thus of the need for application in the current season (Peverill *et al*. 1999; Fageria 2009). The micronutrient status of the current crop is best assessed by using plant tissue tests (Reuter and Robinson 1997), with micronutrients applied as recommended (e.g. Graham 2008). If plant-tissue test results can be returned quickly enough, these micronutrients can be applied as foliar sprays during the season, thereby avoiding GY loss. Tests for P, S and N can also be made and corrective fertilisers applied, particularly for K and S (Anderson *et al*. 2015). However,

Table 1. Estimated plant populations and seed rates for wheat according to target grain yield

Row spacing of 20 cm and average seed size of 35 mg are assumed for the calculations

Target grain yield (t/ha)	Target plants/m^2 (plants/m row)	Establishment (%)	Seed rate (kg/ha)
1	50 (10)	85	21
2	100 (20)	80	44
3	150 (30)	75	70
4	200 (40)	70	100
5	250 (50)	65	135

various commercial models are available for in-crop advice on strategic applications of fertiliser. Commercial fertiliser companies and government advisers use various (in-house) models mainly for N applications (e.g. SyN and NPDecide) in WA, and various models based on APSIM (Keating *et al.* 2003) are available for private agronomists and cropping system advisors. The use and effectiveness of crop models needs to be more widely and objectively assessed.

Tactical foliar application of nutrients

It is generally better to 'feed the roots' rather than the foliage, although a few exceptions exist depending on soil conditions (e.g. Ali *et al*. 2016). In order to clarify the role of foliar-applied nutrients as a means of tactical management, it is important to look at the crop's entire nutritional requirements (Franke 1967).

Foliar applications should not be relied on to correct macronutrient deficiencies in rainfed cereal crops, because soil-applied nutrients frequently give higher GYs (Seymour and Brennan 1995; Abdul *et al*. 2012; Fernández and Brown 2013).

Phosphorus

Foliar application of P is not recommended anywhere in the world, partly because the quantity of P needed, 10–20 kg/ha (see Table 2), makes it difficult to apply as a spray. Chemicals providing <5 kg P/ha rarely correct P deficiency. In addition, some studies have shown that, although the timing of foliar application with inclusion of a surfactant in the P solution is important for absorption of P by wheat leaves, the improved foliar uptake does not lead to an increase in GY (Fernández *et al*. 2014; Peirce *et al*. 2019). Because P is required early in growth and broadcast applications are frequently about half as effective as drilled applications, fertiliser is best drilled at sowing (Jarvis and Bolland 1990). The decision is thus a tactical one made at or immediately before sowing.

Nitrogen

Foliar application of N to cereals has attracted considerable attention (Reeves 1954; Finney *et al*. 1957; Gooding and Davies 1992), particularly applications close to flowering, which increase the number or size of grains in the ear (Bly and Woodard 2003). Urea (CH_4N_2O), urea–ammonium nitrate (NH_4NO_3) solution mixture (UAN), ammonium sulfate (NH_4SO_4), and ammonium nitrate can be applied as spray solution (Fageria *et al*. 2009). However, the amount applied for tactical N applications is limited to the maximum N concentration that can be used without freezing pipes and nozzles, rather than the chemical solubility of the N compounds (~330 g urea/L water, 500 g ammonium nitrate/L water). UAN is a solution containing 420 g N/L water. There is little difference in GY when different N sources are compared on the same rate of N applied (Fageria *et al*. 2009). Generally, under rainfed conditions with terminal drought, low soil moisture during grain-filling limits the potential for increased GY from foliar N application; however, increases in protein content of wheat grain after late application of foliar N have been reported (Reeves 1954). In general, the tactical (or split) application of granular fertiliser can be an effective means of tactical management of N on neutral to acid soil types (see below).

Potassium

If K deficiency is diagnosed by either plant tissue analysis or visual symptoms, K fertiliser can be applied to the soil surface 4–6 weeks after sowing. Foliar sprays generally do not supply sufficient K to overcome a severe deficiency and can scorch leaves of crops in some circumstances. Foliar-applied K, along with other micro- and macronutrients, did not increase the GY of narrow-leafed lupin in WA (Seymour and Brennan 1995).

Some field experiments have evaluated the efficiency of K applied as a foliar spray versus a soil application (John and Lester 2011; Abdul *et al*. 2012; Ali *et al*. 2016; Farooqi *et al*. 2012). A foliar spray of 3% K was more efficient for increasing growth and GY than soil application and fertilisation (Ali *et al*. 2016).

Sulfur

When S deficiency is observed or diagnosed by plant analysis, the usual practice is to apply S fertiliser to the soil surface (Brennan and Bolland 2008). In a 2-year study, Ozanne and Petch (1978) measured GY increases of 22% following foliar fertilisation with a mix of N, P, K and S. However, Seymour and Brennan (1995) found that 4 kg S/ha applied 2 weeks after flowering reduced the GY of narrow-leaved lupin by ~10% (300 kg/ha), despite no evidence of foliar damage. Limited data are available on the effect of S foliar spray for the other crop species grown in rainfed agricultural regions.

Copper (Cu)

Foliar application of Cu can be useful up to flowering if a deficiency has been diagnosed in growing plants (Gartrell 1981). Foliar spray usually contains 10–15 g $CuSO_4.5H_2O$/L water. A single soil application of Cu at recommended rates can provide a longer residual effect for the growing crop, whereas foliar applications generally require consecutive applications. However, foliar Cu sprays are seen as an appropriate response if plant-tissue analysis during the growing season has indicated a Cu deficiency (Gartrell 1981; Brennan 2000). Where crops are grown on subsoil moisture, the topsoil where the Cu fertiliser is placed is frequently dry and the fertiliser is unavailable to root

Table 2. Range of concentrations (kg/t) of nutrients found in wheat grain and straw in Western Australia

	N	P	K	S	Mg	Ca	Cu	Zn	Mn
Grain	16–26	2–3.5	3–7	2–3	1–1.5	0.2–0.4	0.002–0.004	0.02–0.04	0.02–0.05
Straw	2–10	0.2–1.5	6–16	0.4–1.5	0.5–1	0.6–2	0.001–0.003	0.01–0.03	0.01–0.06

uptake, in which case foliar applications are more effective (Gartrell 1981; Grundon 1980).

Zinc (Zn)

Severe Zn deficiency can affect young seedlings, usually in the first 3–4 weeks following emergence (Brennan 1991). Foliar application of Zn helps the remaining seedlings to survive, even if a large percentage of the spray lands on the soil surface. Effects on GY are minimised if foliar-applied Zn is applied immediately symptoms are seen. In situations when Zn deficiency is less severe, foliar sprays are required as soon as symptoms appear or after plant-tissue analysis indicates Zn-deficiency problems.

Manganese (Mn)

In some situations, a foliar spray of Mn is the most effective treatment, particularly on highly alkaline soils (pH >8.5) where Mn is less soluble (Gettier *et al*. 1985). In acid soils, for example in WA, sporadic Mn deficiency occurs in gravelly soils, particularly in drier growing seasons (Smith and Toms 1958; Brennan and Bolland 2011). Patches of crop displaying Mn deficiency can be sprayed with $MnSO_4.5H_2O$, which is a relatively cheap and effective source of Mn.

Manganese is required for the developing seed in pods of narrow-leaved lupin and other grain legumes as the crops mature. During this part of the growing season, the topsoil is frequently dry, and soil-applied Mn is unavailable for uptake by roots. Hence, a tactical Mn foliar spray is effective to overcome Mn deficiency in lupin if the plant is sprayed when the seed pods on the main stem are ~2.5–3.0 cm long. If delayed beyond this time, Mn spraying is less effective (Seymour and Brennan 1995). Manganese deficiency results in split and shrivelled seed within the pods, resulting in GY losses and decreased profits for producers.

Molybdenum (Mo)

Usually fertiliser application of 75–100 g Mo/ha lasts ~10 years in acidic sandplain soils (Doyle *et al*. 1965; Brennan 2006). If Mo deficiency is diagnosed by plant-tissue analyses in crops such as wheat, barley (*Hordeum vulgare* L.) or canola, a solution of sodium molybdate (Na_2MoO_4, 39% Mo) or ammonium molybdate ($(NH_4)_6Mo_7O_{24}$, 54% Mo) applied to the leaves of the plants corrects the deficiency when applied at rates of 0.20–0.40 g ammonium or sodium molybdate/L water. For example, tactical application of foliar Mo sprays at mid-flowering of 40 g Mo/ha overcame Mo deficiency for canola grain production (Brennan and Bolland 2011). However, higher foliar rates of 50–150 g/ha of the Mo sources are recommended for some crop species (Bell and Dell 2008).

Liming ($CaCO_3$) may be required to ameliorate soil acidification in some regions, and this will also alleviate Mo deficiency induced by soil acidification if sufficient lime is added to raise the pH_{Ca} of the top 10 cm of soil to ≥5.5 (Brennan and Bolland 2011). If deficiency of Mo is diagnosed for crops grown on acidic soils, a foliar spray is fully effective if applied at ~20 g Mo/ha.

Boron (B)

Boron deficiency is rare in wheat and other cereals (Brennan *et al*. 2015). In addition, species with a higher requirement for B (e.g. canola and lupin) are usually adequately supplied in the soils of WA, even where soil extractable B levels are low (~0.003 g B/kg in $CaCl_2$ extractant). However, the redistribution of foliar-applied B to actively growing young tissues that require B for growth is limited in most crop species, except lupin. Thus, foliar application of B is of limited use for most crop species even if B deficiency is diagnosed. This suggests that critical soil-test concentrations for crop production need to be defined.

If B deficiency is diagnosed by plant-tissue analysis, B can be sprayed at 0.1–0.5 kg B/ha at the flag leaf stage (Z37–41; Zadoks *et al*. 1974) to increase GY by reducing pollen sterility (Dell *et al*. 2002). However, application of B fertiliser, particularly borax ($Na_2(B_4O_5(OH)_4).8H_2O$), can reduce germination and seedling density (Brennan *et al*. 2015).

Removal of nutrients

One guide for determining rates of fertiliser application needed in the current season is to estimate the likely amount of each nutrient removed in the grain (for wheat, see Table 2; after Gartrell and Bolland 2000). The target GY can then be used as the starting point for estimating fertiliser application rates. Soil type, previous crops and seasonal conditions need to be considered, and local experience at the farm or paddock level, in combination with soil and/or tissue tests, is often used to 'fine-tune' these decisions (e.g. the use of test strips when applying nutrients diagnosed as potentially deficient). Adoption of variable-rate fertiliser technology (Robertson *et al*. 2012) can be a further aid in optimising costs and returns where several sources of information need to be considered.

Tactical N application

Several forms of N have been assessed for tactical application in field experiments in WA, including urea, ammonium nitrate, ammonium sulfate, calcium ammonium nitrate (variable formulations) and anhydrous ammonia (NH_3) (Mason 1968, 1977). The composition of these N fertilisers and current costs should be compared on cost per unit N (Mason 1968, 1977); however, urea is usually the most cost-effective N source for tactical applications. The main benefit of N is to increase the number of ears per ha in cereals (Simpson *et al*. 2016), and the greatest benefit is achieved by applying the N early, especially in short-season environments, so that tillering can be increased (Littler 1963; Ellen and Spiertz 1980). However, the optimum tactic recommended for timing of N applications to annual crops varies, especially according to soil and rainfall conditions (Nordblom *et al*. 1985; Ladha *et al*. 2005). Application of N at sowing appears preferable where the crop is grown largely or partially on stored soil water (Cooper 1974). Application before expected rainfall in addition to a dose of N at sowing also appears advantageous where the soils are unlikely to be prone to nitrate leaching (Anderson 1985; Angus and Good 2004; Simpson *et al*. 2016). In temperate environments with cold winters and relatively reliable precipitation, an appropriate tactical management is to apply the N fertiliser according to the growth stage of the crop (Ellen and Spiertz 1980; Christensen and Mients 1982; Tosti *et al*. 2016). The N status of the crop can be compared with 'adequate' levels from tissue tests as described for local conditions (e.g. Reuter and Robinson 1997; Simpson *et al*. 2016). In the high-rainfall zone of the south of WA, where the topsoils are often sandy and the rain is concentrated in the growing season, it may be appropriate to replace losses due to leaching- and/or waterlogging-induced denitrification after heavy rain events (Simpson *et al*. 2016). Estimates of crop N status in the field have been developed by using methods involving crop-canopy reflectance, leaf transmittance and chlorophyll concentration (Muñoz-Huerta *et al*. 2013). Many commercial, ground-based methods (i.e. Yara N-Sensor, GreenSeeker, CropScan) and satellite-mounted sensors (i.e. QuickBird) measure crop-canopy reflectance in the visible and/or infrared wavebands for the purpose of estimating N in plants (Li *et al*. 2010; Vigneau *et al*. 2011). There is a paucity of data for rainfed crops, and this study suggests that further research is required. The application of tissue tests as an aid in assessing fertiliser requirements can be complicated by competition from weed species such as annual ryegrass (*Lolium rigidum* Gaud.) (Palta and Peltzer 2001).

From a tactical management perspective, the total amount of N required to satisfy the target GY can be estimated at sowing. For example, using information from Gartrell and Bolland (2000), a 4-t crop of wheat would contain 64–104 kg N in the grain and a further 8–40 kg in the straw (Table 2). Part of the total N required can then be applied at sowing, and the remainder applied according to the preferred tactics depending on the soil and weather conditions. One advantage of this application system is that the later applications can be withheld if seasonal conditions do not meet expectations and the probability of reaching the target GY is reduced (Seymour *et al*. 2016; Simpson *et al*. 2016), or if the chance of 'haying off' is increased (van Heerwaarden *et al*. 1998).

Use of tillage in tactical management

Full (mechanical) tillage, which is a tactical means to address short-term issues, is considered one of the oldest methods for controlling weeds, pests and diseases (Yenish *et al*. 1992; Horne and Page 2008; Franzluebbers *et al*. 2011). Disturbance of the soil profile and the removal (by incorporation) of surface plant residues eliminates suitable shelter and host plants for pests (e.g. snails) and reduces the risk of stubble-borne diseases such as net-type net blotch (*Pyrenophora teres* f. *teres*) and spot-type net blotch (*P. teres* f. *maculata*) (Jayasena and Loughman 2001; Horne and Page 2008; Le Gall and Tooker 2017). Tillage distributes weed seeds throughout the tilled soil layer, with the highest concentration of weed seeds generally in the 0–5 cm soil layer (Franzluebbers *et al*. 2011). Seeds of common weeds buried deeper than 10 cm often germinate if sufficient soil moisture is present but they usually fail to emerge. Tillage can stimulate mass germination of weeds such as annual ryegrass and wild oats (*Avena fatua* L.), allowing control of these seedlings with a single herbicide application before crops are sown (Madin 1993; Franzluebbers *et al*. 2011). Full tillage is no longer practiced in many rainfed agricultural areas (e.g. Llewellyn and D'Emden 2009; Yigezu *et al*. 2014; Loss *et al*. 2015), although it does have a place in treating soil compaction (Hamza and Anderson 2005) and managing certain weed species (see below), and it may be used to achieve the above benefits.

Currently, farming systems in the south of WA use minimum or no tillage techniques, and ≥30% of plant residues are retained on the soil surface to reduce water and wind erosion (Derpsch 2003). However, retention of crop residues in rainfed cropping systems in Australia and elsewhere does not appear to have had unequivocal benefit for crop GYs (Scott *et al*. 2010; Loss *et al*. 2015). We conclude that further research is required to delineate clearly the separate effects of reduced tillage and residue retention and to establish the appropriate conditions for full soil disturbance across a range of cropping situations.

The adoption of minimum or no tillage and stubble retention as part of a system of conservation cropping can increase the disease load in paddocks, where some diseases such as such as spot-type net blotch of barley can persist on stubbles such that >2 years is required to reduce the disease burden of the stubble effectively (Jayasena and Loughman 2001). If seeding occurs in ungrazed pastures or if the preceding cereal GY was >1 t/ha, then tillage may still be an option. According to Leonard (1993), cereal paddocks with these GYs are likely to have residues >1.4 t/ha, which contributes to poor crop establishment in the following year. On the positive side, tilling the paddock requires no removal or management of stubble and may lead to better crop establishment. The decision to use deep tillage (inversion ploughing or deep ripping) has often been made by farmers in WA after testing for soil compaction by using an improvised, pointed steel rod.

The impact of tillage systems on soil compaction and its treatment across common soil types has been studied in WA (Hamza and Anderson 2003), with the roles of deep ripping and gypsum application measured. There is probably a further requirement to examine the effects of these strategic practices and their possible interaction with the tactical practices discussed here.

Tactical applications of crop rotation

Crop rotations in which a pasture, pulse or oilseed crop is grown after a cereal crop can significantly influence a range of factors including changes in soil N and management of pests, weeds and diseases. Fixed rotational systems are rarely used, with the final choice influenced by several considerations including short-term fluctuations in commodity prices for grains and livestock (Lawes 2015; Lawes and Renton 2015). If consideration is given to the value of grain from the different crops that are compared in this paper, canola had the highest average price in 2019, at AU$601/t, followed by lupins ($430/t), wheat ($309/t) and barley ($233/t) (Grain Central 2019; Cargill 2020*a*, 2020*b*, 2020*c*). Given the relative prices and expected grain yields of the crops, it is often profitable to have canola in the cropping rotation despite its susceptibility to pests, increased input costs and environmental risks (Kirkegaard *et al*. 2016).

Decisions regarding crop sequences can be made immediately before seeding, but some of the inevitable interactions with the longer term strategic decisions are worth discussing. Canola is often grown as the first crop after a pasture to control weeds and diseases before the cereal phase (Kirkegaard *et al*. 2016). However, pastures sustain higher numbers of pests such as earth mites and weevils that can damage the following seedling canola crop, leading to increased insecticide usage (Micic 2005; Horne and Page 2008). In recent years, the frequency of canola has increased in the rotation, with a similar decrease in pastures, especially in WA. This increase in canola has reflected its profitability as a commodity in its own right as well as a strategy to control weeds and diseases for the following cereal crops (ABARE 2017). The reduced time between canola crops has led to an increase in stubble-borne diseases such as blackleg (*Leptosphaeria maculans*), increases in applications of N and of herbicides to control weeds in the canola phase (see Kirkegaard *et al*. 2016), and increased insecticide usage (Macfadyn and Hill 2017). Where the goal is to maximise profits, there is a need to consider an integrated approach for the management of disease, weeds, pests and fertiliser applications (Brennan 1989; Bockus and Claassen 1992; Doole and Weetman 2009; Nichols *et al*. 2009, 2012).

In WA, disease risk for barley is increased if the crop is grown at intervals of <4 years, but it is more profitable to grow barley with a 2–3-year rotation even if stubble-borne diseases such as spot-type net blotch are an issue (Jayasena and Loughman 2001). Currently, the disease risk for short rotations is high, and this is managed through the use of fungicides to decrease stubble-borne diseases. However, repeated applications of fungicides increase the risk of resistance developing in the disease pathogen. For example, malting varieties of barley have poor resistance to powdery mildew (*Blumeria graminis* f. sp. *hordei*), but owing to market demand, these varieties are most commonly grown with triazole-based seed-dressing fungicides. The pathogen has now developed resistance (Tucker *et al*. 2015), and this can reduce GY by up to 40% if infection occurs before flag-leaf emergence and up to 25% if infection occurs after this time.

Management of the 'green bridge'

Mixed-farming enterprises commonly leave volunteer plants and weeds intact for grazing by livestock during the pre-crop period (hence the 'green bridge'). This practice has implications for insect, disease and weed management (Coutts *et al*. 2018). Feeding of livestock on green weeds and crop stubble can decrease (but not eliminate) disease inocula of, for example, air-borne diseases such as barley leaf rust (*Puccinia hordei*). However, this practice can lead to a decrease in the amount of standing stubble, leading to germinating crops being more susceptible to colonisation by aphids (Jones 1994; Coutts *et al*. 2015).

The success of herbicide applications in controlling a green bridge depends on the weed seedbank that may germinate with subsequent rainfall events, as well as the size of the weeds present at emergence (Walsh *et al*. 2004; D'Emden and Llewellyn 2006; Bastiaans *et al*. 2008). In addition, a green bridge depletes the available stored soil moisture for the subsequent crop (Walsh *et al*. 2004; Bastiaans *et al*. 2008). Application of non-residual herbicides may be needed after each germination of weeds; residual herbicides are not commonly used for summer weed control.

The timing of herbicide applications to control the green bridge is important for reducing numbers of pests and can be as effective as an insecticide application (Macfadyn and Hill 2017). However, the optimum time to apply herbicides is ≥14 days before seeding (Coutts *et al*. 2015). This will lead to a fallow period of at least 10 days before crop emergence, thereby reducing pest numbers. Fast-acting herbicides may be required where timings are tight so that the fallow period is sufficient to stop pests such as aphids or mites transferring from dying plant hosts onto germinating crops.

Weed management

Weed-management decisions are driven mainly by the economic impact of the weed on the current crop, the impact it may have on the following crop, and the propensity for the particular species to develop resistance to common herbicides. The impact on the current crop can be due to competition (e.g. annual ryegrass, Moore 1979), reduction of available soil moisture (e.g. summer weeds), or grain contamination (e.g. by seeds of wild radish (*Raphanus raphanistrum* L.) or sclerotium of ergot of rye (*Claviceps purpurea*)). Thresholds are used to determine when control is required. Weed control based on the impact on following crops is driven by the fact that it is often easier and less costly to control grasses in broadleaf crops, and broad-leaved species in cereal or grass crops. Thus, higher levels of control of wild radish in cereals may be practised if a legume or *Brassica* crop is following. Similarly, high levels of grass control may be practised in broadleaf crops if a cereal crop is planned for the following year. Resistance is another important factor in decision making, especially for annual ryegrass, brome grass (*Bromus rigidus* Roth.) and wild radish. In these cases, growers often opt for maintaining very low levels of the weed in continuous cropping fields in order to reduce the risk of developing resistance to the most economic herbicides.

Overall, the weed species in agricultural ecosystems in rainfed temperate environments tend to be a mix of species of Poaceae (grasses), Asteraceae (daisies and thistles), Brassicaceae (radish, turnips and mustards) and Fabaceae (clovers, medics and grain legumes) (Moore and Wheeler 2020). Profitable crops also tend to come from these families, with wheat, oats (*Avena sativa* L.) and barley from the Poaceae family, canola from the Brassicaceae, and lupins, peas and beans from the Fabaceae. Because these crops are often rotated, the major weeds are often volunteers from the previous crop in addition to the naturalised species (green bridge). In Australia, native plant species are rarely weeds of winter crops but can occur as summer weeds (Moore and Moore 2020).

Because elimination of all weeds and their seeds seldom occurs in the previous growing season, tactical weed management is essential for each growing season and for each crop species. This includes cultural treatments such as cultivation, burning, weed-seed collection at harvest, grazing, rotation and fallow, in addition to herbicide treatments (Dodd *et al*. 1993; Seymour *et al*. 2012; Walsh *et al*. 2017). Insofar as weed management has a tactical component, it can be guided by knowledge of the weed population in the year before cropping and by observation of weed-seedling emergence after the opening rains in the current season (Dodd *et al*. 1993).

Growers may wait for emergence of weeds before spraying with non-selective (knock-down) herbicides if there is an early break to the season. This application may be repeated in 3–14 days with a follow-up spray before sowing the crop. If there is a late break to the season, growers may sow the crop before the rains arrive (dry seed) and apply residual herbicides before sowing or after sowing and before crop emergence. Selective herbicides can then be used once the crop has established. In these situations, growers may also opt to switch to herbicide-tolerant crop varieties so that glyphosate, imidazolinones or triazines may be applied to the crop after emergence. The particular herbicides used depend on the crop, weeds, tillage system (as some herbicides require incorporation), and resistance status of the weeds—in particular annual ryegrass, which has widespread resistance to the Group A ('fop' and 'dim' grass-selective) and Group B (sulfonylurea broad-spectrum) herbicides. Typical mixtures and sequences of herbicide application are summarised for the major crops in 'Favourite Brews 2020.pdf' in Moore and Moore (2020). In most cases, this will include herbicides that provide good control of weeds from the Asteraceae, Brassicaceae, Fabaceae and Poaceae families. Computer models such as HerbiGuide and HerbiRate are used tactically to adjust herbicide selections or rates of application on the basis of local conditions (Moore and Minkey 1997; Moore and Moore 2020). Several other models are rarely used by growers but are good educational aids to demonstrate principles of weed control and agronomic interactions (e.g. Legizamon *et al*. 1980; Grundy and Mead 1998; Monjardino *et al*. 2003; Jones *et al*. 2005; Somerville *et al*. 2018).

Biological control agents have been released against several weeds with varying effects. Common heliotrope (*Heliotropium europaeum* L.), doublegee (*Emex australis* Steinh.), fiddle dock (*Rumex pulcher* L.), Paterson's curse (*Echium plantagineum* L.), skeleton weed (*Chondrilla juncea* L.) and various thistles are agricultural weeds that have been targets for bio-control, using a range of agents including rusts, beetles, mites, midges, moths, flies and weevils (Dodd *et al*. 1993). Because their level of bio-control varies from season to season, tactically applied supplemental control is often used. This area needs further investigation.

Minimum tillage is the most common planting practice in broadacre, rainfed cropping systems in Australia (Anderson *et al*. 2005). This can be related to various combinations of increasing costs of cultivation; decreasing costs of herbicides, insecticides and fungicides; larger farm sizes and machinery; risks of erosion; and difficulty in attracting labour during peak periods. However, it may complicate weed management.

Management practices

Tactical practices may include:

- Changes in weed control in leguminous crops and pastures based on price movements of N or grains.
- Changes in weed control so as to vary the carryover of weed seed into the following season, based on changes in predicted relative prices of crops versus livestock in the following season where crop weeds are the main pasture species.
- Timing of weed control, with early control generally giving higher GY than late control. Seasonal conditions will influence timing and products used for early control, and late germinations of weeds that cause grain contamination may necessitate a later spray.
- Herbicide rate adjustment to take account of current environmental conditions (Minkey and Moore 1996) or weed density (Moore and Moore 2020).
- Use of a 'base recipe' for the crop (Moore and Moore 2020) or advice from a consultant. Many growers then adjust this for tactical management of specific weeds or where herbicide resistance occurs. The base recipe usually contains herbicides or practices that control the major families of weeds to reduce the risk of minor weeds predominating in response to the weed control implemented.

Both pre-emergent and post-emergent herbicides are extensively used as are residual and non-residual herbicides in the Australian rainfed cropping systems (Moore and Moore 2020).

Pre-seeding and pre-emergent practices

In addition to practices of summer weed control and reduction of the green bridge to conserve moisture and reduce effects of disease, insect and allelopathy, several tactics are imposed close to seeding.

Growers generally wait for a germination of weeds before spraying with glyphosate, or less commonly, they use paraquat or paraquat + diquat mixtures as the knock-down herbicide. Trifluralin is often added as a pre-emergent herbicide before seeding common crops such as cereals, canola or legumes. Atrazine and simazine are commonly used residual herbicides before seeding lupins and triazine-tolerant canola. Imidazolinone herbicides are used on Clearfield varieties of cereals and canola, and various speciality herbicides are used in crops such as chickpea (*Cicer arietinum* L.), faba bean (*Vicia faba* L.) and lentil (*Lens culinaris* Medik.) (Moore and Moore 2020). In paddocks with a high weed burden, a shallow cultivation may be used to encourage the weeds to germinate, thereby allowing greater control with the knock-down herbicides.

If the rains at the start of the season are 'late', the tactics used include seeding crops into dry soils with knock-down herbicides, replaced by residual herbicides such as atrazine for triazine-tolerant varieties of canola or imidazolinone herbicides for Clearfield or imidazolinone-tolerant varieties. Cereals and conventional varieties of canola may be sown following the application of trifluralin herbicide, and a tactical decision may be made to add a more soluble product such as metolachlor or to top-up after the rains. Where herbicide resistance is found, active ingredients such as *pyroxasulfone* (Sakura, Bayer CropScience) may be substituted for trifluralin before seeding cereals (Moore and Moore 2020).

Post-emergent herbicides

Various post-emergence selective herbicides are commonly used in cereals, and many contain MCPA (a Group I herbicide) mixed with products such as bromoxynil, diflufenican, picolinafen, terbutryn, pyrasulfotole, linuron or diuron, from other herbicide groups (Moore and Moore 2020). The choice of herbicide is usually a tactical decision based on the species and densities of the weeds present at the two-leaf to tillering stages of the crop.

Hormone herbicides such as 2,4-D are still widely used, whereas the use of Group B herbicides has decreased as herbicide resistance in the major weeds (i.e. annual ryegrass and wild radish) has developed (e.g. Owen *et al*. 2014). Most growers will inspect the crop at 6–8 weeks after germination and make a tactical decision on the need for follow-up herbicide application based on the degree of weed control achieved and the level of late germinations.

Many growers have management practices in place to reduce the risk of herbicide resistance developing. These practices include rotating between herbicide groups, using non-chemical methods of weed control, maintaining low weed densities, sowing clean seed, and actively controlling patches of weeds that appear to be resistant. About three-quarters of annual ryegrass populations are resistant to commonly used Groups A and B herbicides (Owen and Powles 2018). In paddocks with high weed burdens, glyphosate-tolerant canola varieties may be planted and glyphosate applied post-emergence. Failures of weed control due to resistance are usually remedied with tactical application of an alternative herbicide, or a decision to cut the crop for hay rather than allowing it to progress to grain harvest.

Non-chemical weed control

Non-chemical methods for weed management include:

- Tactical shallow cultivation to encourage weed germination when the break of the season occurs at least 1 week before the planned planting date.
- Inversion (mouldboard) ploughing in areas with high levels of herbicide resistance, or in combination with other practices such as the redistribution of nutrients and lime or reducing non-wetting.
- Concentration of chaff and harvested weed seed into narrow windrows behind the harvester.
- Tactical burning of stubbles or harvest windrows when conditions allow.
- Weed-seed collection at harvest by using chaff carts or stubble balers, based on the weed-seed set in the paddock or price of stubble.
- Harvest weed-seed control, using various machines that damage seed as it leaves the harvester (Walsh *et al*. 2017). These are turned off in areas that are relatively weed-free.

Herbicide resistance

Owen and Powles (2018) have reported high levels of resistance to Groups A and B herbicides in ryegrass and wild radish in many cropping areas of Australia. Populations resistant to other commonly used herbicide groups also occur, but at very low levels. Tactical decisions are taken to manage these populations with other herbicides or control methods (Dodd *et al*. 1993). Despite high levels of resistance, growers are maintaining adequate levels of weed control (Owen and Powles 2018). Many growers have adopted practices that are applied tactically over the cropped areas to minimise the risk of herbicide resistance.

Other factors influencing weed control decisions

Tactical control of particular weeds is practiced for a variety of other reasons in rainfed agricultural systems including:

- Control of capeweed (*Arctotheca calendula* (L.) Levyns), thereby reducing the effects of redlegged earth mite (*Halotydeus destructor* (Tucker)) and vegetable weevil (*Listroderes difficilis* (Germain)) on canola.
- Control of small crumbweed (*Dysphania pumilio* (R.Br.) *Mosyakin & Clemants*) and stinkwort (*Dittrichia graveolens* (L.) Greuter) to reduce allelopathy in following crops (Moore and Moore 2020).
- Summer weed control to conserve soil moisture (Bastiaans *et al*. 2008), reduce disease levels, and reduce insects including caterpillar pests such as pasture webworm (*Hednota* spp.), mites and molluscs.

In conclusion, we argue that growers are managing weed populations to levels that are not having a major impact on GY. Further research on optimising weed control would lead to greater profitability, because many weed-control decisions are driven by risk aversion rather than cost effectiveness. Biosecurity is an area that also requires ongoing support to protect the industry from new threats such as Star of Bethlehem (*Ornithogalum umbellatum* L.), three-horned bedstraw (*Galium tricornutum* Dandy), skeleton weed (*Chondrilla juncea* L.) and other undetected species. Although there are policies to control new invasive species, rapid tactical responses are required on discovery. Market access also needs continuing research to ensure that residue levels of herbicides and pesticides are kept at acceptable levels and other contaminants such as ergots and ryegrass toxicity are minimised.

Insect pests

Tactical management of insect pests relies on frequent field observation in the current season (counts of invertebrate numbers and/or damage assessments to plants) when weather conditions are likely to favour the pests, and use of control measures when thresholds are reached. Some thresholds can be related to environmental conditions that favour multiplication of some insect species (Nichols *et al.* 2009).

Current pest-management practices in commercial systems

Tactical control of agricultural pests in Australian pastures and cropping environments relies heavily on pesticide applications (Micic *et al.* 2008; Umina *et al.* 2011), which are routinely applied as a prophylactic spray for the control of pests regardless of pest densities (James 2000; Macfadyn and Hill 2017). In WA, prophylactic sprays tend to be applied with herbicide applications either pre-seeding or before crop emergence, in order to control potential early-season pests (Gu *et al.* 2007; Micic *et al.* 2007; Lawrence 2009). Dependence on pesticides for insect control is not a new phenomenon. In 1959, VM Stern and colleagues (cited in Stern 1973) highlighted that insecticides were being applied without any understanding of the density at which pests caused economic injury to crops.

Thresholds that have been developed for pests of rainfed crops can be used to determine whether a pest needs to be controlled. If thresholds are used in combination with biological, cultural and chemical controls to decrease pest densities (i.e. integrated pest management, IPM), then pesticides are applied only when pest numbers exceed economic thresholds (Fick and Power 1992; Flint and Gouveia 2001; Flint *et al.* 2003; Edwards *et al.* 2008; Horne and Page 2008). However, the uptake and use of thresholds by farmers depends on the threshold being based on current research and taking into account the crop's ability to tolerate damage. If the assessment methods needed to monitor for the threshold are too time-consuming, then prophylactic insecticide applications are more likely to occur (Gu *et al.* 2007; Leather and Atanasova 2017; Ramsden *et al.* 2017). Thresholds for some pests are shown in Table 3. In some cases, there are a number of thresholds for the same pest in the same crop, highlighting the need for a more coordinated approach for determining thresholds (e.g. Ramsden *et al.* 2017).

Integrated pest management

Reviews of IPM in Australia highlight its success in controlling pests in cotton and horticulture (see Williams and Il'ichev 2003; Gu *et al.* 2007; Horne *et al.* 2008; Hoy 2011). However, there are very limited examples of its success as a tactical management method in rainfed agriculture (Hoffmann *et al.* 2008). Horne *et al.* (2008) suggest that one of the factors responsible for poor adoption of IPM is

Table 3. Some insect pests of rainfed crops and their control thresholds

Pest group	Species	Threshold	Citation
		Canola	
Acarina: Penthaleidae	Redlegged earth mite, *Halotydeus destructor* (Tucker)	10 mites/plant with a true leaf	Arthur *et al.* 2015
Collembola: Sminthuridae	Lucerne flea, *Sminthurus viridis* (L.)	10 holes/leaf	Macfadyn and Hill 2017
Homoptera: Aphididae	Cabbage aphid, *Brevicoryne brassicae* (L.); turnip aphid, *Lipaphis erysimi* (Kalt.)	20% of racemes with aphids	Edwards *et al.* 2008
Lepidoptera: Plutellidae	Diamondback moth, *Plutella xylostella* (L.)	200–300/m^2 at flowering and podding	Dosdall *et al.* 2011
		2–3 larvae/plant at podding	Canola Council of Canada 2014
		100 larvae/10 sweeps at flowering, 200 larvae/10 sweeps at podding	Micic 2005
		Wheat and barley	
Homoptera: Aphididae	English grain aphid, *Sitobion avenae* (Fitch); rose-grass aphid, *Metopolophium dirhodum* (Walker)	2–4 aphids/tiller at flowering, 6–10 aphids/tiller up to milky ripe stage, ≥10 aphids/tiller from milky ripe to medium-dough stage	Johnston and Bishop 1987
	Corn aphid, *Rhopalosiphum maidis* (Fitch); oat aphid, *Rhopalosiphum padi* (L.)	50% of tillers with ≥15 aphids	Michael 2002
	Sitobion avenae	5 aphids/ear before flowering or 75% of tillers infested	Dewar 2017
	Prevention transmission of virus by *Sitobion avenae*, *Rhopalosiphum padi*	Spray if aphids present	Ramsden *et al.* 2017
	Rhopalosiphum maidis, *Rhopalosiphum padi*	If virus risk is high, use seed dressings or a two-spray tactic	Michael 2002
Lepidoptera: Noctuidae	Southern armyworm, *Mythimna convecta* (Westwood); sugarcane armyworm, *Leucania stenographa* (Lower); southern armyworm, *Persectania ewingii* (Westwood); inland armyworm, *Persectania dyscrita* (Common)	Barley: 3 large caterpillars/m^2 at head ripening	Grimm 1995
		Wheat: 10–25/m^2	Moore and Moore 2020

that researchers have concentrated on a single pest and have not dealt with all of the pests in a crop. They also found that growers did not have the confidence to not apply a spray application for pests in crops such as canola and legumes.

For early-season pests (i.e. pests that affect crops at the seedling stage), the disadvantages of using a single 'count' threshold for a single pest can be overcome by applying an insecticide based on the amount of plant damage occurring to the crop at establishment (~14 days after germination) (e.g. Arthur *et al*. 2015). This approach relies on identifying pests that are present in a paddock from their feeding damage to the crop, and then applying an appropriate insecticide only if the crop is likely to fall below the optimum density for GY. For instance, for canola the target density should not be <20 plants/m^2 (DPIRD 2019), for narrow-leaved lupin 35 plants/m^2 (O'Connell *et al*. 2003), for barley 120/m^2 (Paynter *et al*. 2019), and wheat 100 plants/m^2 (Anderson *et al*. 2004) depending on target GY (see Table 1).

However, this approach requires use of a higher seeding rate to allow for some seedling loss. For instance, before hybrid canola seed was available, the recommendation was seeding at 5 kg/ha to establish ~50 seedlings/m^2 (Micic 2005). However, the cost of hybrid canola seed is $34–48/ha, based on a seeding rate of 2 kg/ha (Seymour 2011), which leaves only 30 seedlings/m^2. Optimal seedling density is 25 plants/m^2 with conventional varieties and $\geq$30 seedlings/m^2 with hybrid varieties (Seymour 2011). Consequently, a prophylactic spray of α-cypermethrin at 400 mL/ha, which costs ~$4.00/ha (Moore and Moore 2020), is an attractive option compared with reseeding a crop or increasing the seeding rate.

Tactical management for late-season pests such as diamond back moth (*Plutella xylostella* (L.)) and the armyworm complex (see Table 3) relies on monitoring crops until it is too late in the season to apply insecticides before harvest (Miller and Pike 2002; Floate and Hervet 2017). Crop monitoring can be time-intensive. The use of sweep nets to detect the presence of lepidopterous pests is a more time-efficient method than observing single plants. However, sweep nets are limited to the edges of crops such as canola owing to the difficulty of entering the crop at flowering (e.g. Floate and Hervet 2017). Sweep-net counts cannot be related to the density of the pest per plant (e.g. Dosdall *et al*. 2011); consequently, for the same pests there are different thresholds based on the monitoring technique used (see Table 3). The timing of crop monitoring needs to coincide with the presence of the pest in the landscape. This knowledge can be achieved through the use of pheromone traps or forecasting based on environment (e.g. Thackray *et al*. 2004; Harrington *et al*. 2007; Dosdall *et al*. 2011).

Timing of insecticide applications

Insecticides are usually applied when pests either cause sufficient plant loss or are at a threshold to cause yield loss. However, by understanding the lifecycle of pests, tactical control measures can be applied to suppress populations before egg laying occurs. For instance, the pest species most damaging to germinating canola in WA was the redlegged earth mite (Ridsdill-Smith *et al*. 2008). This mite hatches from over-summering eggs when there is sufficient moisture and when at least 7 days have elapsed with mean temperatures <20.5°C, with peak hatchings occurring in mid-May (Wallace 1970). This can coincide with the germination of seedling crops such as canola (Kirkegaard *et al*. 2016). One of the main recommendations for the suppression of redlegged earth mite for a pasture–canola cropping rotation is to apply control measures to pasture during spring. The timing of this spray will kill the female mites before over-summering eggs can be produced (Ridsdill-Smith *et al*. 2008) and leads to lower mite numbers in the following canola crop. However, in WA there has been a move from seeding canola in June to earlier in April (Glen 2000; Kirkegaard *et al*. 2016) so that crop germination is less likely to coincide with peak hatchings of redlegged earth mites.

However, early-autumn sowing means that temperatures can be milder and pests such as aphids (e.g. green peach aphid, *Myzus persicae* (Sulzer)) that are usually found in crops in spring are now present on seedling canola (Coutts *et al*. 2015; Macfadyn and Hill 2017). Aphids such as green peach aphid are resistant to many insecticides and can spread *Turnip yellows virus*, causing GY losses of 30% in canola crops if infected at the seeding stage (Coutts *et al*. 2015; de Little *et al*. 2017). Instead, the use of insecticide seed treatments is recommended to decrease the incidence of this aphid pest spreading virus to germinating crops (Coutts *et al*. 2015).

The use of insecticide seed treatments as a tactic to suppress pests has very low non-target effects and is compatible with an IPM framework (Williams 2017). However, insecticide seed dressings can have limitations in protecting seedlings from pest damage if pest numbers are high. For instance, seed dressings containing the active ingredient imidacloprid are only successful if mites such as redlegged earth mite are present in low densities (i.e. at thresholds of 10 mites/100 cm^2) (Horne and Page 2008; Moore and Moore 2020).

Varietal selection

Selection of varieties that are resistant to pests and diseases is an important tactical management practice. Some crop cultivars have aphid resistance (e.g. Adhikari *et al*. 2012; Brewer *et al*. 2019); however, to date there are no commercialised varieties of canola, cereals or lupins with resistance to herbivorous invertebrates. There is some evidence that different varieties have different tolerances to damage (e.g. Liu and Ridsdill-Smith 2001). Even so, if crop varieties are chosen that match the predicted growing season and have good disease tolerance, crops are likely to be healthy (Williams 2017) and thus more likely to outgrow feeding damage, especially from establishment pests.

Implications for grain contamination

Invertebrate contaminants do not cause any injury to the grain but are incidentally harvested with the grain. There is a need to ensure high-quality grain for export; therefore, grain receival points have limits on the amount of contaminants. If this limit is exceeded, growers must arrange for their grain to be cleaned

(Moore *et al*. 2019), an expense that is picked up directly by the grower. A tactical response to decrease contamination risk is to change time of harvest or harvest technique. For instance, if harvest occurs in the middle of the day when invertebrates are not actively moving there is less invertebrate contamination of grain; if crops are direct-harvested and not swathed, there is less contamination (Micic and Michael 2005; Micic *et al*. 2006).

Future implications for pest management

In dry conditions, farmers are more likely to dry-seed crops, with germination occurring as soon as there is sufficient soil moisture; this is a widespread practice in low-rainfall areas globally (ABARE 2017). Crops germinate with the first opening rains, which can coincide with warmer weather, leading to potentially moisture-stressed crops that are more susceptible to pest damage if insufficient follow-up rainfall occurs. Currently, the only tactical option if crop loss is occurring is to apply insecticides.

Longer term strategic management needs to focus on suppressing pest populations before they can cause crop damage regardless of the season. This can be achieved only by using cultural controls and requires forward planning because it cannot be applied in the year that economic damage is observed. Routine prophylactic spraying will increase the risk of insecticide resistance. This may be addressed by further research and extension on the economic effect of invertebrate pests on GYs and the efficacy of control measures.

Disease management

Management of the common diseases of the principal crops produced in winter-dominant rainfall regions often involves both tactical and strategic practices. Soil-, stubble- and air-borne diseases affect cereal crops grown in rainfed agricultural regions. The leaf diseases mostly require high humidity and either rainfall or dew on the leaves for germination of disease spores when the atmospheric temperatures are optimum, and wind for dispersal of spores (e.g. Jeger *et al*. 1981; Te Beest *et al*. 2008). Some examples are shown for barley (Table 4) and wheat (Table 5), indicating the specificity of the various diseases and the tactical management for them. Awareness of these factors is important for effective disease management tactics, but this may be further complicated by the different responses of some genotypes to environmental factors (Hogg *et al*. 1969; Garrett *et al*.2006).

Table 4. Optimum conditions for infection of common leaf and stem diseases of barley and some methods used for tactical management

Disease	Conditions required for disease development	Tactical methods
Scald (*Rhynchosporium commune*)	10–20°C (Skoropad 1960) Humidity >92% for 2 days (Ayesu-Offei and Carter 1971)	Seed treatment (Khan and Young 1988) Barley grass control (Burdon *et al*. 1994) Use of resistant varieties (Paynter *et al*. 2019) Rotation (Khan 1988) Foliar spray (Khan 1986) Avoiding use of excess N (Jenkins and Jemmett 1967)
Net-type net blotch (*Pyrenophora teres* f. *teres*)	Infected seeds (Shipton *et al*. 1973) High humidity up to 30 h and temperature 10–25°C (van den Berg and Rossnagel 1990)	Rotation and grazing (Khan and D'Antuono 1985; Khan 1986, 1988) Use of resistant varieties (Paynter *et al*. 2019) Seed-dressing fungicides (Platz *et al*. 1999) Delayed sowing (Delserone and Cole 1987) Avoiding use of excess N (Piening 1967) Foliar fungicides (Shipton 1966; Thomas *et al*. 2008)
Spot-type net blotch (*P. teres* f. *maculata*)	Similar to net-type	Rotation and stubble management (Brown *et al*. 1993; Duczek *et al*. 1999; Jayasena and Loughman 2001) Grazing (Hills and Paynter 2012) Avoiding use of excess N (Piening 1967) Adequate K fertiliser (Brennan and Jayasena 2007) Delayed sowing (Khan 1989)
Powdery mildew (*Blumeria graminis* f. sp. *hordei*)	High relative humidity 15–22°C (Mathre 1997) >25°C inhibits infection (Mathre 1997)	Use of resistant varieties (Paynter *et al*. 2019) Control of barley volunteers (Limpert *et al*. 1999) Use of seed dressing (Tucker *et al*. 2015) Foliar fungicides (Jayasena *et al*. 2006; Hills and Jayasena 2013) Adequate K fertiliser (Brennan and Jayasena 2007) Reducing use of N fertiliser (Bainbridge 1974; Hills and Paynter 2007)
Leaf rust (*Puccinia hordei*)	~20°C for urediniospore production (Simkin and Wheeler 1974) Free moisture (6 h at 100% relative humidity and 22°C for maximum urediniospore germination) (Simkin and Wheeler 1974) Latent period decreases urediniospores as ambient temperature increases from 10°C to 25°C (Teng and Close 1978)	Use of resistance varieties (Wallwork *et al*. 1992; Paynter *et al*. 2019) Time of sowing (Jayasena *et al*. 2018) Seed dressings (Jayasena *et al*. 2018) Fungicide sprays (Jayasena *et al*. 2018) Green bridge control (Coutts *et al*. 2018)

Table 5. Common leaf and stem diseases of wheat, their conditions required for disease development and some methods of tactical management.

Disease	Conditions required for disease development	Tactical methods
Rusts: • Stem rust (*Puccinia graminis* f. sp. *tritici*) • Leaf rust (*P. recondita* f. sp. *tritici*) • Stripe rust (*P. striiformis* f. sp. *tritici*)	Stem rust: • Optimum temperature for disease development ~24°C and reduced development <15°C (Murray *et al*. 2009) • Leaf wetness essential for spore germination (Murray *et al*. 2009) Leaf rust: • Overnight dews and optimum temperature between 15–22°C (Murray *et al*. 2009) • Leaf wetness essential for spore germination (Murray *et al*. 2009) Stripe rust: • Temperature 10–15°C, humid with dew or rain provides optimum conditions for disease development (Murray *et al*. 2009) • Temperature >25°C limits disease development	Management practices adopted for three rusts are similar: • Control of green bridge (Park 2008) • Use of resistant varieties (Park 2008) • Early warning systems and fungicide sprays (Loughman *et al*. 2005; Beard *et al*. 2018*a*)
Powdery mildew (*Blumeria graminis* f. sp. *tritici*)	Breezy conditions with high relative humidity Temperature 15–22°C favourable Temperature >25°C and high rain less conducive and will inhibit development (Murray *et al*. 2009)	Controlling volunteer wheat (Beard and Thomas 2018) Crop rotation (Beard and Thomas 2018) Avoid early sowing (Murray *et al*. 2009) Use of fungicides (foliar or seed) (Thomas *et al*. 2017; Beard and Thomas 2018) Use of resistant varieties (Golzar *et al*. 2016; Zaicou-Kunesch *et al*. 2018) Avoiding excess use of N (Beard and Thomas 2018)
Septoria blotch (*Parastagonospora nodorum*)	High rainfall High relative humidity for 6–16 h and 20–27°C required for optimal spore production and germination (Murray *et al*. 2009)	Crop rotation and stubble management (Francki *et al*. 2011) Use of resistant varieties (Solomon *et al*. 2006) Fungicide sprays (Solomon *et al*. 2006) Adequate K nutrition (Cunfer *et al*. 1980; Beard and Thomas 2018)
Septoria tritici blotch (*Zymoseptoria tritici*)	Mild wet conditions (Hess and Shaner 1987*a*, 1987*b*) Temperature 15–20°C favourable (Murray *et al*. 2009)	Crop rotation and stubble management (McDonald and Mundt 2016) Avoiding early sowing (Eyal 1999; McDonald and Mundt 2016) Use of resistant varieties (Gigot *et al*. 2013; Shackley *et al*. 2020) Fungicide sprays (Marroni *et al*. 2006) Avoiding excess use of N (Eyal 1999) Adequate K nutrition (Arabi *et al*. 2002)
Yellow spot (*Pyrenophora tritici-repentis*)	Wet weather Optimum temperature 20–28°C (Murray *et al*. 2009)	Use of resistant varieties (Shankar *et al*. 2015) Crop rotation (Salam *et al*. 2013) Avoiding early sowing (Wilson 1989) Stubble management (Salam *et al*. 2013) Increasing K, avoid using excess N (Beard *et al*. 2018*b*) Fungicide spray (Bhathal *et al*. 2003; Salam *et al*. 2013)

For stubble-borne diseases, the disease profile must be known. This entails knowledge of the diseases present in the paddock in the previous year and the susceptibility and tolerance of the crop that is to be grown in the current year. For air-borne diseases, the farmer also needs to know what diseases were prevalent in the previous season, the disease risks from any green bridge, and especially the diseases found upwind from the current crop.

Decision-support tools for disease management are limited and require development for necrotrophic pathogens such as septoria, net blotches and scalds, and biotrophic diseases such as powdery mildew. PREDICTA B is a support tool that is increasingly used for detection of soil-borne diseases (Ophel-Keller *et al*. 2008).

Variety selection

The use of resistant or tolerant varieties is the most economical way to manage disease in rainfed crops. Although growing resistant varieties does decrease disease risk, varieties also need to be high yielding for farmers to grow them. A single variety will not be resistant to all diseases present in the region; therefore, understanding the disease risk before sowing the crop is important for variety selection and disease management. Disease incidence varies with season, and variety susceptibility may also interact with seasonal influences. Variety selection can be facilitated through the yearly publication of variety sowing guides (e.g. Paynter *et al*. 2019; Zaicou-Kunesch *et al*. 2018) when the disease-resistance profile of varieties is known. However, this information is not always available and is a major research requirement in some regions.

The use of seed that has been certified free of relevant diseases, where available, can decrease seed-borne disease risk. For instance, every 1% of grain infected by loose smut leads to a 1% GY loss (Hills 2018). Those seeds need to be treated with fungicidal seed dressings to prevent further infection. As a minimum measure, farmer experience shows that knowing the provenance of imported seed is advisable if farm-saved seeds are not used.

Time of sowing

Sowing time can be altered to manage some crop diseases. For instance, in the southern parts of WA, spore showers of yellow spot (*Pyrenophora tritici-repentis*) occur in early April and May, and wheat crops sown at this time are most susceptible. If crops are sown later, disease risk is reduced. However, in northern areas of WA, yellow spot spores mature after the end of May and crops sown at this time are most at risk (Galloway *et al*. 2016).

Crop nutrition

Growing a healthy crop reduces some disease risk. For instance, incidence of barley powdery mildew and spot-type net blotch can be reduced by up to 40% in crops that have sufficient K. The combination of adequate K nutrition with foliar fungicides can further significantly reduce the impact of these diseases on GY (Brennan and Jayasena 2007). Conversely, application of high rates of N can promote the incidence of barley powdery mildew (Bainbridge 1974; Hills and Paynter 2007). However, late-season urea sprays can assist suppression of disease in winter wheat in some environments (Gooding *et al*. 1988).

Chemical control

If resistant varieties are not present for all common foliar diseases, fungicidal seed dressings can be used or fungicide can be applied in-furrow with the fertiliser at seeding. If seeds are not treated with fungicide, the seedling crop can be sprayed with a foliar fungicide. In modern cropping systems, farmers may focus on varieties with high GY irrespective of disease profile and may become heavily reliant on fungicide control. There is a need to consider an integrated approach to reduce reliance on fungicides so that these chemicals can remain effective in the future.

Implementing integrated control

Different diseases are controlled by different management practices. Examples of the components of integrated control measures for the major diseases of barley and wheat are summarised in Table 4 and 5 below.

*Take-all (*Gaeumannomyces *spp.)*

Take-all is a soil-borne root disease of wheat, barley, rye and oats, and is common in high-rainfall areas such as in the southern region of WA (MacLeod *et al*. 1993). It is caused by *G. graminis* vars *tritici* and *avenae*. Take-all is more severe in sandy, alkaline, infertile soils and exacerbated by continuous cropping, early sowing and poorly drained soils. The pathogen survives in summer in the cereal residues of the previous growing season's grass hosts. The symptoms can be first noticed when premature plant death occurs during grain-filling, resulting in development of 'white heads'. The affected plants often occur in conspicuous, circular patches in the field. Soil temperatures in the range 10–20°C are optimal for infection. Higher rainfall during winter favours early infection by the disease, but late infection near crop maturity has less impact on GY because infection is confined to roots.

Long-term continuous cereal cropping has been shown to decrease take-all over time (Kwak and Weller 2013; Lawes *et al*. 2013). Benefits arising from reduced take-all may be offset, however, by the economic losses arising from continuous cereal cropping (Loughman *et al*. 2000).

There is no varietal resistance available against take-all disease. Therefore, managing take-all relies primarily on cultural practices to prevent survival of the fungus between seasons. Practices such as eliminating grass hosts and use of non-cereal break crops (lupins, canola, field pea (*Pisum sativum* (L.)) in rotation can reduce carry-over of the disease between seasons. Minimising crop residues can also reduce take-all. However, no-till farming practices, which have been widely adopted to increase accumulation of organic matter and prevent soil erosion, serve to increase take-all. Burning the stubble can reduce the amount of infected surface residues but is not effective in eliminating the infected materials below the ground level.

Concluding remarks

Economic considerations

The ability to respond to weather conditions during the growing season may be complicated in the field by other limiting factors, especially soil physical problems. Farmers in both traditional and modern cropping systems may use conservative management practices and alter inputs in response to uncertain weather conditions and economic returns (e.g. Kingwell *et al*. 1993; Yigezu *et al*. 2014). However, when the causes for suboptimal performance are not fully understood, a process of diagnosis of the problems through local experimentation may well point the way to profitable GY improvement (Anderson *et al*. 2014).

The tactical management factors identified in this review all have a cost, or range of costs, and an anticipated benefit if effective. The impact on GY of each individual limiting factor can be estimated as a starting point for estimating the benefit and cost of remediating the factor. Comparisons of the range of benefits for the wheat crop from the tactical management factors can be made by examining published GY losses arising from individual limiting factors, along with some likely costs of treatment, possible benefits, and thus net benefits (Table 6). These costs are based on published values in the Australian literature, which in themselves show some variability. However, the remediated GYs in each of these publications were at, or close to, the estimated rainfall-limited potential GY in each case. In other regions where socioeconomic conditions may differ, the values listed in Table 6 should be used only to assess likely relative benefits of remediating the various limiting factors, rather than as absolute values.

The data in Table 6 indicate that improving management of factors such as sowing time, nutrient application, or control of diseases, pests and weeds present at damaging levels can return far more to the farmer than changing the crop cultivar. This finding is similar to findings of Kirkegaard *et al*. (2014) in Australia and Piggin *et al*. (2015) in in northern Syria. However, many farmers prefer to adopt new crop cultivars rather than addressing other management factors, possibly because of the lower cost, logistical considerations such as availability of machinery, or not having the skills or confidence to implement other changes. The difficulty of resolving such tactical decisions in an environment where profit margins are small could be assisted by development of a simple decision aid (or crop model) based on the research discussed in this review. This decision aid could include an indication of the likely sequence of decisions and their linkage to seasonal conditions such as rainfall, temperature and humidity.

The issue of the potential overuse of chemical methods to manage the various biotic factors that can impact crop production cannot be ignored if sustained increases in productivity of rainfed systems are to be achieved. Increasing evidence of genetic resistance of various weed species to various chemicals (e.g. Owen and Powles 2018) is one particular challenge for researchers continuing to develop new, integrated systems that can be sustained into the future. The costs and ultimate benefits of developing integrated pest, weed and disease management systems requires further research, development and extension in order to achieve sustainable rainfed cropping systems (e.g. Nordblom 2003). The costs of remediation of these in-crop challenges relative to the potential benefits are quite small (see Table 6), so farmers tend to apply measures on the basis of very simple field observations rather than more detailed, randomised counts as might be appropriate for experiments.

Implications

Although the classical agronomic questions regarding practices such as sowing times, seed rates, and weed, disease and pest management have largely been addressed for the major cereal crops such as wheat and barley, widely applicable information is less available for the pulse crops and canola. The questions that remain are centred on integration of these practices with the longer term strategic issues largely involving soil improvement and crop rotations. Although we have confined our review to tactical management, there is a need for further examination of possible synergies between tactical, strategic and genetic methods in lifting average GYs. The relevance of research findings can be extended by using multi-site and multi-factor field experiments, for which there is a long tradition in Australia (e.g. French and Schultz 1984). Where it is desirable to add value to such data through development of crop models and decision aids, reliable field data can be invaluable for validation.

Many leading farmers have adopted the relevant research findings and their crop GYs are approaching the potential (e.g. Kingwell *et al*. 1993; Abeledo *et al*. 2008; Hochman *et al*. 2012; Robertson *et al*. 2012; Kirkegaard *et al*. 2014). Reasons for average or poorer GYs may be more related to operational convenience, availability of machinery, skills, and attitudes to economic risk rather than to maximising profits *per se* and they remain a challenge for researchers and advisers. Application of the findings regarding tactical management as outlined in this review can provide only a part of the solution to the problems that can be diagnosed on individual farms or soil types

Table 6. Factors limiting grain yield of rainfed crops (wheat or barley), the likely losses, potential costs of remediation and possible net benefits.

Limiting factor (and reference)	Loss of grain yield (t/ha)[A]	Cost of remediation ($/ha)[B]	Net benefit ($/ha)[C]
Late sowing (Sharma *et al*. 2008)	0.9	50	211
Low seed rate (Anderson *et al*. 2004)	0.5	25	120
Inappropriate cultivar (Anderson *et al*. 2011)	0.2	25	33
Micronutrient deficiency (Zn) (Brennan 1991)	1.0	15	275
Macronutrient deficiency (P) (Brennan 1989)	0.8	70	162
Loss of grain yield due to N leaching (Simpson *et al*. 2016)	1.6	120	344
Inappropriate weed management (Moore 1979; Moore and Moore 2020)	1.0	20	270
	1.2	30	318
Inappropriate disease management (Loughman *et al*. 2005)	0.6	37	137
Inappropriate insect management (Michael 2002; Murray *et al*. 2012)	0.4–1.8	12	104–510

[A]Difference between measured yield and calculated rainfall-limited yield, calculated as: seasonal rainfall – (seasonal rainfall/3) × 20.
[B]Earlier sowing cost (e.g. extra weed control $50, purchase of new seed $0.5/kg).
[C]Calculated at $290/t farm gate price (i.e. wheat price – average freight and tolls) and $1/kg for N fertiliser.

(e.g. Anderson *et al*. 2014). The onset of widespread climate change in the form of declining rainfall and changes in seasonal rainfall distribution (Stephens and Lyons 1998) is one of the main stimuli for reviewing some of the known means of addressing these changes.

Conflicts of interest

The authors declare no conflicts of interest.

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