Canola integration into semi-arid wheat cropping systems of the inland Pacific Northwestern USA

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Abstract. The inland Pacific Northwestern USA (iPNW) wheat-producing region has a diversity of environments and soils, yet it lacks crop diversity and is one of the few semi-arid wheat-growing regions without significant integration of oilseeds. Four major agroecological zones, primarily characterised by water availability, feature distinctly different fallowed and annually cropped systems, each presenting different challenges and opportunities to integrate winter and spring canola. Although major interests in regional energy crops and rotational diversification spurred feasibility research on iPNW canola food, feed and fuel production in the 1970s, commercial canola adaptation has lagged behind other semi-arid wheat regions for various socioeconomic, ecophysiological and agronomic reasons. New federal crop insurance policies will reduce economic risks in new crop adaptation, and oilseed processing facilities are creating new local markets. Although canola management largely relies on wheat farm equipment, agronomic approaches require strategic adjustments to account for physiological differences between canola and cereals including seed size, seedling morphology and responses to temperature extremes. Climate change predictions for the region threaten to exacerbate current hot and dry summers and research aims to develop and adapt flexible winter and spring canola-based systems to regional water and temperature stressors in each zone. Adaptation will require novel planting, fertilisation and weed control strategies to successfully establish improved winter canola cultivars in hot dry summers that survive cold winters, and spring canola cultivars direct-seeded in cool wet springs. The adaptation of winter and spring canola will somewhat mirror the rotational placement of winter and spring cereals within each zone. Economic analysis of oilseed break crop benefits such as weed and disease control will help to demonstrate the medium-term economic benefits of crop diversification to support the growth of a regional canola industry in the iPNW.

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Potential for canola adaptation in the iPNW region

Over the past 125 years, eastern Washington and surrounding areas of Oregon and Idaho, USA have been highly monocropped in a wheat-fallow system (Schillinger and Papendick 2008) with limited diversification using cool-season legumes. The inland Pacific Northwest (iPNW) has distinct cropping zones defined by precipitation, temperature and soils (Douglas et al. 1990). A dominant east–west decreasing precipitation gradient has dictated the evolution of four major wheat-dominated agroecological zones (Fig. 1) across northern Idaho to central Washington and Oregon (i) annual cropping zone (>450 mm annual precipitation); (ii) annual crop–fallow transition zone (300–450 mm annual precipitation) (iii) grain-fallow zone (<300 to mm annual precipitation) and (iv) irrigated zone of central Washington and Oregon (Huggins et al. 2014). Analysis of USDA NASS interpreted satellite survey datasets have provided current updates and refinements of zonal estimates of annual land areas (Table 1), and crop identities (Huggins et al. 2015). There is limited crop diversification within each of these wheat- and fallow-dominated rain-fed zones, in contrast to the greater diversity of the row-cropped areas of the irrigated central basin of Washington and Oregon (Fig. 2). Interests in energy crops and rotational diversification spurred feasibility research on iPNW canola production and end-use 40 years ago (Divine et al. 1977). Agronomic and variety performance field trials were then conducted by the regional land grant universities (Bettis and Auld 1980; Porter et al. 1981; Kephart 1986; Gareau et al. 1990; Johnson and Lewis 1995), later coupled with Brassica agronomy, breeding and variety testing (Brown et al. 1995) and engineering programs (Bettis et al. 1982; Petersen 1984) at the University of Idaho. Although research has continued to demonstrate the potential to grow improved winter and spring canola cultivars in different iPNW subregions (Brown and Davis 2015), commercial production has lagged behind other global regions due to systemic agronomic, economic and marketing constraints. Canola yield instability and lack of regional canola industry infrastructure and markets were considered major reasons for the slow adoption.
Renewed interest and government support for canola production in 2007 lead to state supported investments in research and extension programs (Sowers and Pan 2014). Between 2011 and 2014, iPNW-harvested canola area increased from 14 000 to 38 000 ha (USDA 2015). Although the current production is roughly equivalent to the current oilseed crushing capacity recently established in Washington state, another 10-fold increase in production is required to match the potential regional oilseed refining capacity for food, fuel and feed production, equivalent to ~10% of the total row-cropped area of the region (Lang 2014; Table 1).

Canola has been effectively integrated into semi-arid wheat-cropping systems of western Canada, Western Australia and the Great Plains of the USA. The crop diversification with break crops has effectively improved the agronomics and economics of these systems (Zentner et al. 2002; Conley et al. 2004; Kirkegaard et al. 2008a; Seymour et al. 2012; Angus et al. 2015). Rotational benefits from insertion of an oilseed crop into a...
wheat production system are numerous, including breaking
disease, weed and insect cycles (Kirkegaard et al. 2008a). The
iPNW has similar needs and opportunities for diversification
that could include oilseed integration (Cook et al. 2002; Young et al. 2014). Primary agronomic benefits motivating
iPNW growers include prospects for improved weed control,
improved nutrient cycling and water use, and improved soil
quality.

There are both similarities and differences between the
climate and soils of the iPNW and those of other major semi-
arid canola-producing regions of the world, including Western
Australia, the western Canadian prairie, and the Great Plains of
central USA (Table 2). Maximum growing-season temperatures
can subject canola to heat stress coupled to limited water
availability in all four global regions. Western Canada is least
subject to maximum temperatures and most subject to minimum
temperatures, with regional rankings of average minimum
temperatures: western Canadian prairies < Great Plains USA <
iPNW < Western Australia. As a result, only spring cultivars are
grown in the spring and summer of the Canadian prairies, the
coldest of these regions, but also in the winter of Western
Australia, the warmest of these global regions. Due to the
more moderate temperatures of the Great Plains and iPNW,
both winter and spring cultivars can be grown during the
respective seasons in various subregions and harvested in
summer. Canola is similar to wheat in that it has both winter
and spring types, where the winter types have a vernalisation
requirement. Winter types of wheat (Schillinger et al. 2010a)
and canola (Pakish et al. 2015) typically out-yield their spring
counterparts in this region due to their longer growing season,
more efficient utilisation of winter precipitation with deeper
roots and earlier grain filling. However, winter canola is
limited to rotations and zones in which there is a suitable
period with conditions for successful establishment and winter
survival.

The iPNW also has a high proportion of annual precipitation
received during the winter months during winter canola
ormancy (Table 2). The majority of precipitation in the
iPNW is a mixture of snow and rain, often over frozen soils.
As a result, crops are more reliant on stored water and nutrients
in the subsoils for sustaining growth and development from
stem elongation through grain development. As <40% of the
total annual precipitation is received during the spring and
summer months, climate-induced water and heat stress occurs
during reproductive stages of development. Fortunately, the
aeolian and glacial, medium-textured soils are generally deep
to bedrock with high water-holding capacity (Schwartz and
Alexander 1995) ranging from 270 to 360 mm in a 180-cm
profile (Table 2). This is in contrast with canola grown during
the wet winter in Western Australia, where climate-induced
water stress may still be an issue during the reproductive
stages during drought years. The highly weathered soils of the
region, many with poor physical structure, root restricting
compaction (Lisson et al. 2007; Smettem and Gregory 2010)
and low (34–134 mm) water-holding capacity (Oliver and
Robertson 2009) exacerbate these problems (Hamza and

\[ \text{Fig. 2.} \quad 2007–2013 \text{ average land areas and crop distributions across four agroecological cropping zones in iPNW. (Huggins et al. 2014).} \]

\[ \text{Table 2.} \quad \text{Climate and soil characteristics of established and emerging canola production areas in semi-arid regions (6–8 sites) of the world} \]

<table>
<thead>
<tr>
<th>Area</th>
<th>Minimum temperature (°C)</th>
<th>Maximum temperature (°C)</th>
<th>Annual precipitation (mm)</th>
<th>% Precipitation during growing season</th>
<th>Soil water-holding capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland PNW\textsuperscript{A}</td>
<td>–7° to –3°C</td>
<td>28–32°C</td>
<td>260–660</td>
<td>20–40</td>
<td>135–360 mm (Schwartz and Alexander 1995)</td>
</tr>
<tr>
<td>Canadian Prairies\textsuperscript{A}</td>
<td>–22°C to –11°C</td>
<td>22–27°C</td>
<td>300–450</td>
<td>60–67</td>
<td>50–250 mm (De Jong and Shields 1988)</td>
</tr>
<tr>
<td>SW Australia\textsuperscript{C}</td>
<td>–2°C to 4°C</td>
<td>21–34°C</td>
<td>260–650</td>
<td>65–75</td>
<td>34–134 mm (Oliver and Robertson 2009)</td>
</tr>
</tbody>
</table>


Anderson 2003), and all contribute to potential drought stress. The Great Plains of the USA and western Canadian soils have variable water holding capacity (50–350 mm) and a higher percentage of precipitation during the growing season compared with the iPNW (Table 2).

The greatest agronomic challenges in fostering iPNW canola adaptation are to define wheat–canola-based rotations that improve weed control, optimise soil water and N recovery, and crop use, establish good plant stands, maximise plant survival during overwinter freezing and early spring frosts, and sustain crop water and nutrient use during hot, dry summer months. The diversity of environments, soils and cropping systems across the four major iPNW production zones (Fig. 1, Table 1) present challenges to design suitable wheat–canola cropping systems within each zone. The overarching goal of the Washington State Oilseed Cropping Systems project is to integrate appropriate winter and spring canola cultivars into cropping systems tailored for each of these zones to increase crop and market diversification and productivity. The agronomic research aims to identify appropriate crop sequences and modifications to traditional wheat crop establishment and fertility management strategies to accommodate differences in physiological and morphological traits of canola relative to wheat.

Annual crop zone

Rotational fit. The annual cropping zone comprises 568 000 ha of the Palouse and western foothills of the Rocky mountain range, straddling the eastern Washington–Northern Idaho border (Table 1, Fig. 1). Precipitation of >450 mm per year supports annual cropping, with winter wheat, spring wheat and spring barley grown over 60% of the cropping zone land area and cool-season legumes account for only 18% (Fig. 2.). Typically, there is insufficient soil moisture and growing degree-days following crop harvest to establish and grow winter canola to sufficient size before freezing winter conditions, so the focus is on adapting spring canola (discussed below), substituting spring cereals or legumes in the rotation (Table 1). Winter canola is more feasible following fallow, but fallow is not normally practiced in this region (Fig. 1) unless wet spring conditions prevent establishment of spring crops. Nevertheless, surviving winter canola in this zone can yield 3000–4000 kg ha⁻¹ with ample available soil moisture (Brown and Davis 2015; Evans et al. 2015).

Weed management. The predominance of cereal crops in this zone encourages annual grassy weed infestations such as Italian ryegrass (Lolium multiflorum Lam), downy brome (Bromus tectorum L.) and jointed goatgrass (Aegilops cylindrica HOST; Ball et al. 1999). Increasing broadleaf crops in rotation with wheat provides better control of these grassy weeds, particularly when herbicide-resistant canola is used (Young et al. 2016). Nine years of substituting glyphosate-resistant spring canola for spring legumes in rotation with winter and spring cereals was effective in controlling Italian ryegrass in farm-scale strip trials near Pullman, Washington (Huggins and Painter 2011). The inclusion of glyphosate-resistant spring canola also controls troublesome broadleaf weeds such as mayweed chamomile (Anthemis cotula L.) and common lambsquarters (Chenopodium album L.) that are difficult to control in cool-season food legumes. A wide selection of spring canola cultivars are available in the iPNW to deal with, depending on individual circumstances including resistance to glyphosate, glufosinate, and imazamox. Generally, a grass herbicide such as quizalofop should be added to a glufosinate-resistant variety to improve grass control. Hybrid spring canola has become available in the region, and has been demonstrated in western Canada to have higher yield potential, which likely imposes greater N requirements than an open-pollinated line (Mahli et al. 2007; Smith et al. 2010).

If fallow is dictated by poor spring crop seeding conditions, early seeding winter canola into fallow, a regional condition called ‘delayed planting’ does offer the opportunity to apply the dual-purpose canola concept (Kirkegaard et al. 2008b; Neely 2010) by taking advantage of the biennial characteristic of winter canola cultivars to produce forage and grain from a single planting. In an on-farm experiment, in the annual cropping zone, winter canola intercropped with spring pea and planted on 2 July, produced 780 kg DM ha⁻¹ forage that was harvested 2 September, 70 days after seeding (Kincaid et al. 2011). The forage was made into high quality silage feed for dairy cows. The cut plants then re-generated a smaller, lateral shoot-producing plant supported by the established root system. These plants survived the winter, subsequently producing 2000 kg grain ha⁻¹ the following season, demonstrating that growth of a strong root system with reserve energy and nutrients is more critical than having an abundance of shoot biomass for winter survival. Cutting canola shoot meristems theoretically removes a source of auxin, inhibiting lateral shoot stem initiation and development (Lia et al. 2016), which may provide a mechanism for more vigorous post-winter regrowth.

Plant establishment. Winter wheat can be successfully established in this zone with adequate autumn precipitation following summer harvest of a winter or spring grain crop because only a small seedling is required to survive the winter (Young et al. 2008). In contrast, establishment of winter canola in similar annual crop rotations has proven difficult, due to prevalent dry soil conditions that delays timing of germination until there are insufficient growing degree-days for establishing plants of sufficient size to overwinter (Murray and Auld 1986; Moore and Guy 1997; Holman et al. 2011). Post-harvest precipitation required to initiate seed germination and seedling growth typically does not occur until temperatures are too cool to foster adequate seedling root and shoot biomass production needed to overwinter during sub-freezing conditions. As a result, winter oilseeds do best when planted into higher surface soil moisture in fallow in this zone, as demonstrated in winter rape (Brassica napus) planted between 31 July and 5 September, producing yields ranging from 3800 to 4670 kg ha⁻¹ near Moscow, Idaho (Murray and Auld 1986). Yet the fallow period required to establish winter canola in the high rainfall zone would waste a growing season in which a marketable crop would otherwise be grown.

Spring canola establishment must be accomplished in heavy winter wheat residue that can range from 6900 kg ha⁻¹ (Papendick and Miller 1977) to 14 500 kg ha⁻¹ (Young et al. 1990), as maintaining these surface residues in direct-seed systems is needed to prevent soil erosion. These high residues reduce seedling growth by maintaining cold soil temperatures
(Pan et al. 1991), which might deter growers from producing spring canola the following year unless the fields have been burned. A 2-year study was conducted examining the effect of 25-cm and 50-cm row spacing on spring canola yield. Each year spring canola was planted at 5.6 kg ha$^{-1}$ in winter wheat residue that had yielded ~6700 kg ha$^{-1}$ of grain. When averaged over site-years, spring canola yield was similar (1710 kg ha$^{-1}$ for 50-cm rows; 1775 kg ha$^{-1}$ for 25-cm rows) regardless of row spacing (Young 2012). With wide row spacing, machine and fuel costs are reduced because of the reduction in openers and subsequent reduction in tractor horsepower. Additionally, it is likely that delays at seeding caused by blockages of high residue loads under seeding equipment (‘drill plugging’) will be reduced with wider row spacing.

Although early spring planting of canola can be a challenge, late seeding also has its penalties. Stands of spring canola are also more consistent when planted before moisture levels decline as spring rainfall is generally sporadic in the region. Spring canola direct-seeded into heavy wheat residue over 9 years showed an inverse relationship between seeding date and grain yield (Huggins and Painter 2011; Fig. 3). As in other canola-growing regions, later plantings result in flowering and grain development under conditions of higher water and temperature stress that reduce grain yield (Gan et al. 2004; Kirkegaard et al. 2016).

**Nitrogen management.** The N management approaches must be tailored to the unique environment of the iPNW. Regional yield-based N recommendations for wheat are commonly calculated by applying a single or narrowly defined unit N requirement (UNR) of 4.5 kg N per 100 kg grain for soft wheat to 6 kg N per 100 kg grain for hard wheat (Koenig 2005; Koenig et al. 2011). However, contrary observations of varying UNR across variable Palouse landscapes have been observed (Fiez et al. 1995) suggesting a more tactical approach to N management could be implemented.

Over 6 years, higher overall UNR of 7–13 kg N (100 kg grain)$^{-1}$ were observed for spring canola in the zone across years varying in water availability. This range is similar to those found in canola fertiliser guides from semi-arid western North America (Pan et al. 2016), and that of 7–8 kg N (100 kg grain)$^{-1}$ in Australia (Norton 2016). Canola plant nutrient uptake per unit yield is higher than soft white and hard red wheats (Koenig et al. 2011), suggesting higher levels of available nutrients supplied by native soil, fertiliser carryover or newly applied fertiliser are required for regional canola production compared with wheat nutrient management. In southwestern Australia, the amount of N fertiliser required to produce optimum yield was 40% higher for canola than wheat (Brennan and Bolland 2009). Nevertheless, canola has a deep taproot system (Gan et al. 2009), as well as extensive root hairs, for fully exploiting soil nutrients and water (Hammac et al. 2011). As a result, canola seed yield responds well to applied N when residual soil levels are low but minimal fertiliser N response when soil N supply is high and yield potential is low (Fig. 4, Pan et al. 2016). This exponential, diminishing-returns response to total available N was also observed in southwestern Australia (Seymour et al. 2016). In Montana, canola responded strongly to fertiliser N when planted into low levels of residual soil nitrate (90 cm depth), where yields were optimised at 200 kg N supply ha$^{-1}$ (Jackson 2000). However, the magnitude of response is variable in the iPNW due to interacting factors of climate, available soil N, cultivar, and management practices. Overall, although spring canola N supply (soil + fertiliser N) requirements per unit grain weight are higher than wheat, its extensive and efficient roots utilise deep residual soil N to 120 cm in this zone to reduce fertiliser N requirements (Maaz et al. 2016).

**Annual crop–fallow transition zone**

**Rotational fit.** The iPNW transition zone is ~665 000 ha, with annual precipitation ranging from 300 to 450 mm and is characterised by annual cropping during wetter than normal precipitation years, interspersed with fallow during drier years (Table 1, Fig. 1). Growers traditionally have grown winter wheat and barley in >50% of the zone, fallow in 27%, and spring legumes in 10% of the zone. In higher than normal precipitation years, continuous crop rotations have been grown. Plant establishment of winter canola or spring canola are both possible in this zone, with opportunities and constraints

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**Fig. 3.** Direct-seeded spring canola yields following spring wheat at Pullman, WA, over 9 years as related to planting date (Huggins and Painter 2011).
described in the above and below sections on the annual crop and crop–fallow zones.

Flexible decisions on planting spring canola in this zone should be based on over-winter soil water storage to 120 cm rooting depth and weather predictions for in-season precipitation. Generally, spring canola yields are correlated with total available water, with water-use efficiency (WUE) slope of 3.25 kg yield mm⁻¹ available moisture in the inland Pacific Northwest (Pan et al. 2016), which is lower than those reported in Australia. Robertson and Kirkegaard (2005) evaluated 42 datasets of dryland spring canola for WUE and found that the WUE of canola varied from 4 to 18 kg ha⁻¹ mm⁻¹, in which later sown crops tended to have lower efficiencies. Similarly, the WUE of spring canola decreased from 12 to 2 kg ha⁻¹ mm⁻¹ when seeded in early winter rather than in early spring within the Mediterranean type environment of Iran (Faraji et al. 2009). Terminal heat and drought stress during the reproduction development may cause the reduction in WUE in late seeded spring canola. Therefore, the WUE of spring canola in the inland Pacific Northwest is more comparable to Canada, where studies report a range of 2.80–5.76 kg ha⁻¹ mm⁻¹ for rain-fed spring canola sown in the spring season (Azooz and Arshad 1998; Cutforth et al. 2006; Gan et al. 2009).

Weed management. A farm-scale rotational experiment at the Washington State University Wilke Farm located at Davenport, Washington, has compared fallow systems with two or three crops with continuous cropping in replicated strips across a variable field (Esser and Hulbert 2013). Herbicide-resistant spring canola cultivars were included in the 4-year rotation, which thus far has enabled the best control of feral cereal rye (Secale cereale L.), resulting in the highest economic return over input costs among the three rotations. Spring canola planted at 5.6 kg seed ha⁻¹ yielded 784–1960 kg grain ha⁻¹ following spring wheat. Rotational wheat yield increases due to improved weed control following canola can result in higher rotational profits, even without economic benefits of canola in single season crop comparisons (Connolly et al. 2016). In certain years of relatively high canola : wheat price ratios, economic benefits have been obtained even without including rotational benefits.

Nitrogen management. Spring canola N response trials at the same location had maximum yields averaging 1027 kg ha⁻¹, and economically optimal N rates averaged 23 kg N fertiliser ha⁻¹, ranging from zero fertiliser N required after fallow to 6–65 kg fertiliser N ha⁻¹ required following wheat (Pan et al. 2016). The higher required economic N rate for canola following winter wheat was evident despite the lower available soil water, and lower canola yield potential. These findings corroborate statements in Alberta Agriculture and Rural Development (2004) about lower N availability following continuous cropping versus fallow. These modest fertiliser N requirements, seemingly contrary to spring canola’s relatively high unit total N supply requirements, are due to high residual soil N carryover and N mineralisation, coupled with canola roots extracting water and N from 90 to 120-cm depths. Overall, the UNR observed in the transition zone ranged from 9 to 17 kg total N supply/100 kg grain, higher than the range (3.9–8 kg total N supply/100 kg grain) reported in fertiliser guides from semiarid western North America (Koenig et al. 2011). This was due to lower yields and NUE of this region, and our more complete accounting of root zone residual N supply and crediting soil N mineralisation contributions to total N supply (Pan et al. 2016).

Grain–fallow zone

Rotational fit. The crop–fallow zone usually has insufficient annual precipitation (<300 mm) to economically support annual cropping (Young et al. 2015), and comprises an area roughly equivalent to the total of the other two rain-fed zones of ~1 245 000 ha. Winter wheat has greater yield potential than spring wheat due to deeper roots, more efficient water extraction, and earlier flowering and grain development during hot dry summer months. Similarly, spring canola is not commonly grown in this zone because spring canola yields only 50–60% as much as winter canola (Paniksh et al. 2015).

Weed management. Weed control in summer is typically accomplished using tillage with a rod weeder or chemical fallow-direct seeding to reduce wind erosion (Young and Thorne 2004). One of the primary reasons to grow winter canola is to offer growers an added management tool to control weeds. Winter annual grass weeds, including feral rye, downy brome, jointed goatgrass, and Italian ryegrass continue to plague monoculture winter wheat growers. The introduction of imidazolinone-resistant wheat in 2003 (Ball et al. 1999) provided growers with an additional option to manage these pests; however, an imidazolinone-resistant biotype of downy brome has been found in Oregon and feral rye is one of the most difficult winter annual grass weeds to control with imazamox (Pester et al. 2000). Feral rye is a predominant winter annual grass weed in the low rainfall, grain fallow region of the iPNW. In this region, quizalofop in conventionally bred winter canola cultivars, for example Amanda, Falstaff, and glyphosate in glyphosate-resistant canola cultivars, for example Croplan 115 and 125, effectively controlled feral rye (Young et al. 2016). A second reason to introduce winter canola into cereal production systems regardless of rainfall zone is availability of herbicide-tolerant canola cultivars. These cultivars allow producers to plant in fields with a history of sulfonylurea, for example Croplan 115 or 125 and imidazolinone herbicides, for example Clarenden and Edimax (Young et al. 2016) without enduring 9–40 months of plant back restrictions. Commercial hybrid cultivars have recently been introduced into this region, and their potential advantages over open pollinated lines are being evaluated in regional trials. For example, winter canola comparisons in Oklahoma have characterised greater seed size and yield potential under optimal conditions, but less drought tolerance than open-pollinated cultivars (Bushong 2015).

Plant establishment. Winter canola establishment is a significant challenge in this zone. The smaller seed size of canola alters seed zone requirements for optimal germination and emergence compared with wheat, which in turn can affect depth of planting. This need for deep planting is greatest in this zone, where late summer high temperatures and little to no precipitation drives the soil moisture line into the subsoil (Schilling et al. 2010a). The range of seed sizes in canola far exceeds that of the variation in wheat seed. Wheat seed planted in the iPNW typically ranges from 31 to 38 mg seed⁻¹, whereas...
canola seed ranges from 2 to 6 mg seed\(^{-1}\) (F. L. Young, pers. comm.). A 3-fold variation in canola seed size makes it more imperative to get accurate oilseed weights when targeting specific plant population goals. Seed size is affected by cultivar and the seed production environment as well as commercial seed sizing processes (Lamb and Johnson 2004). Smaller seed reserves of energy and nutrients of individual canola seeds restrict deep seed placement. Winter wheat cultivars grown in the fallow zone are bred to emerge from very deep seed placement (Mohan et al. 2013). In contrast, canola seed generally emerges best when placed within 2–3 cm of the soil surface when moisture conditions are adequate, but can emerge from deeper placement (3–6 cm) when required to reach moisture. Hypocotyl length is genetically modulated, indicating potential for future breeding opportunities (Zhao et al. 2013). Larger seeds can generally emerge from greater depths due to longer and more robust hypocotyls. In addition, larger seeded Brassica cultivars produce greater early season biomass, which increases crop competition with weeds (Harker et al. 2015; Brill et al. 2016).

Winter canola establishment requires excellent soil moisture near the soil surface and cool (≤29\(^\circ\)C) ambient air temperatures for 5–7 days after planting (Young et al. 2014). Deep furrow drills that are used in the wheat–fallow zone for placing the seed into soil moisture are also being used successfully to plant winter canola as the seedlings need to emerge only to the bottom of the furrow. During August, the optimal time to plant winter canola (Young et al. 2014), soil moisture is usually 10–15 cm below the soil surface and too deep for canola seedlings to emerge. To help alleviate this problem, seedlings 25–38 cm wide have been placed in front of the openers to reach soil moisture and move the hot, dry soil from the furrow, thus reducing the distance the emerging seedling has to travel through the soil (Young et al. 2008, 2014). The use of shovels did not increase winter canola yield and winter survival but did increase plant density 22% compared with when shovels were not used. In addition, there is a more uniform plant distribution from the use of shovels, which suppressed weed growth and reduced weed competition (Young et al. 2014). Generally, a 4.5-kg ha\(^{-1}\) seeding rate was optimal for sufficient stand establishment and yield. When winter canola seeding was delayed until September, yield was decreased almost 40% compared with an August planting. Winter survival can range from 56% to 83% with a subsequent spring plant population of only 20–40 plants m\(^{-2}\) needed for optimum yield.

Spring canola, despite the lower yield potential, can be grown following failed winter canola survival, and glyphosate-resistant spring canola cultivars are beneficial for controlling summer annual broadleaf weeds in this zone such as Russian thistle (Salsola tragus), which emerges with similar timing as spring canola. Spring canola seed broadcast on the soil surface yields between 31% and 67% of spring canola that was placed in the soil with drills equipped with double disk, chisel, hoe, or inverted T-slot openers (Young et al. 2012). Broadcast yields of spring canola were low because generally <5% of the seed established plants. When left on the soil surface, seedlings were unprotected when emerging from the seed coat and were killed by frost. Rolling broadcast seed with a heavy cast-iron roller generally improved yield ~35% compared with broadcast alone although improved yield ranged from 0% to >100%. Depending on location and precipitation, optimum yields ranged from 615 kg ha\(^{-1}\) to 1575 kg ha\(^{-1}\) (Young et al. 2012). Precipitation during flowering and seed-fill in May and June correlated with increased canola yield, presumably by reducing moisture stress during reproductive growth as observed by Gan et al. (2004).

Shoot meristematic origins of dicotyledonous oilseeds differ from monocotyledonous cereal grain crops. Leaves and shoot branch initiation of oilseeds occurs at or near the soil surface (Thomas 2003). In contrast, shoot tiller and root meristems of wheat seedlings emanate at the belowground crown and stem nodes directly above the crown (Klepper et al. 1984). The development of aboveground shoot meristems of oilseeds versus belowground shoot nodes of cereals is a fundamental difference in freeze avoidance (Thomas 2003). Oilseeds are exposed to sudden downturns in air temperatures above the soil surface during late falls and winters, whereas cereals are more protected by the soil layer above the cereal shoot meristem that buffers against rapid and severe subfreezing spikes.

The size of winter canola plants entering the winter months correlates with winter survival. Small seedlings with 2–3 true leaves survive iPNW winters very poorly. This limits winter canola production in the non-irrigated annual cropping zone of the iPNW as very dry soils following harvest of the previous year’s crop generally persist into October; by the time sufficient moisture has accumulated to establish a stand, the seedlings are typically too small to survive the first hard frosts. When planted into fallow land, early planted winter canola takes advantage of added growing degree-days to produce more shoot and root biomass before winter dieback. Planting five winter rapeseed cultivars in the annual cropping zone (600 mm) from 2 July to 13 September indicated that later planting dates resulted in less winter survival and seed yield (Porter et al. 1981), presumably because late season plantings had less energy and nutrient reserves. In contrast, early plantings of winter canola in the wheat–fallow zone take advantage of surface soil moisture, but may result in poor winter survival. Winter cultivars remain vegetative without stem bolting; however, vegetative biomass of early planted canola extracts most of the available soil moisture to 150 cm depth, producing weakened, drought-stressed plants, with higher shoot meristems that were more susceptible to winter kill than later seeded plants (Reese 2015).

Several fields of winter canola were monitored over 3 years across the iPNW, illustrating temperature profiles associated with partial and complete canola winter kill (Fig. 5). In the winter of 2013–2014, minimum temperatures at the soil surface fell to −20°C in early December and again in February, resulting in widespread, complete winter kill across the region. In contrast, minimum surface temperatures only reached −15 to −17°C in January of 2011–2012 and 2012–2013 following gradual temperature declines, which resulted in partial stand losses of −28% to −49%, but still yielding 1700–4300 kg ha\(^{-1}\) even at sites with reduced stands. Winter canola grown in semi-arid environments has the ability to compensate for stand losses with increased stem branching and pod retention (Angadi et al. 2003). A late spring frost in late April–May
during flowering (data not shown) severely reduced the pod set, resulting in yields <1000 kg ha$^{-1}$ despite good stand survival in some locations. This freeze sensitivity of canola coming out of winter dormancy has been noted in the USA Great Plains (Holman et al. 2011). In a location near Davenport, Washington, spring frost was not a factor and winter canola direct seeded into winter wheat stubble averaged 4100 kg ha$^{-1}$ (Schillinger 2013).

Moderation of extreme subfreezing conditions by soil at depths 10–20 cm were consistently demonstrated (Fig. 5) in comparison to surface temperatures, illustrating the morphological advantage of wheat’s ability to develop subsurface shoot meristems that are insulated by soil (Klepper et al. 1984) in comparison to above surface canola shoot meristems. Canola nutritional status potentially contributes to supercooling by increasing cell solutes such as high K and Cl nutrition (Evans et al. 2015). Ensuring a sufficient P status of vegetative canola plants entering into the winter season with the addition of starter phosphorus at planting has been shown to improve winter survival (Wilkins et al. 2002).

Nitrogen management. The N placement and timing for winter canola require additional adjustments from traditional N fertilisation methods used in winter wheat production due to interspecies differences in root architecture. Chemical fallow-direct seeded winter wheat is typically fertilised in deep bands below the seed row at planting (Veseth et al. 1986). Canola seedlings produce a single taproot main axis with lateral roots and root hairs emanating from an ammonia sensitive tap root (Madsen et al. 2014). In contrast, monocotyledonous cereal crops have multiple seminal axes and shoot tillers which initiate from the seed, the belowground crown and stem nodes that produce shoot tillers and affiliated root seminal axes (Klepper et al. 1984). As a result of these basic root architectural differences, canola seedlings are more sensitive than cereals to chemical toxicities such as expanded zones of high ammonia around fertiliser bands due to oilseed reliance on the development of a single tap root, whereas cereals have numerous seminal axes to explore deep soil layers. This basic morphological difference has implications for differential fertiliser band sensitivity: when a canola taproot radicle encounters a high ammonia band, meristems become necrotic with subsequent seedling injury or death (Madsen et al. 2014). While a seminal root axis of cereal seedlings can suffer the same fate, other seminal axes of the same seedling will grow to the side of the band and successfully develop. The ability of wheat roots to morphologically overcome ammonia toxicity of deep banded ammonium fertilisers has allowed the development and commercial use of direct seed planting equipment with deep banding capabilities (Veseth et al. 1986). However, canola’s taproot sensitivity to deep placed ammonia bands will require alternate N placement and timing strategies. Fertiliser placement studies on canola have demonstrated the need to place N as a side band (Grant et al. 2011; Norton 2016).

High N status of the vegetative winter oilseed plants has reduced survival during freezing conditions (Rathke et al. 2006). There are biochemical and morphological responses to high N availability that may contribute to the decrease in winter hardiness. Canola leaves subjected to low temperature stress increase levels of cryoprotectant chemicals (Janská et al. 2010) such as soluble sugars that facilitate cytoplasmic freezing point depression (Gusta et al. 2004). Identification of cultural practices and variety selections for plant survival to rapid

![Fig. 5. Temperature profiles were continuously recorded over three winters at Davenport, WA from 2012 to 2014 in the transitional crop–fallow zone where winter canola is being grown. Air and soil temperature probes in each year were positioned directly above the soil surface or below the soil surface at a depth of 10–15 cm.](image-url)
freeze events may be important to winter canola production in the iPNW, as demonstrated in December 2014 when a rapid freeze resulted in widespread loss of winter canola and winter wheat (J. Schibel, pers. comm.).

Low N status promotes increased sugar concentrations and increased freeze resistance in plants (Lemoine et al. 2013; Wisniewski et al. 2014). As a result, this potentially changes the N timing strategy for managing canola relative to traditional wheat N management in the iPNW. In zones less than 600 mm annual precipitation where nitrate leaching below 180 cm soil depth is typically not excessive, winter wheat N application occurs pre-plant during summer fallow or at planting in annual crop rotations (Veseth et al. 1986; Halvorson et al. 1999). The main reason is to ensure adequate time for fertiliser N to nitrify and move into the lower layers of the root profile, ensuring adequate N availability as the surface soil dries, and plant roots become increasingly reliant on subsoil N (Pan et al. 2001). If low N canola has higher winter survivability, it may provide another reason to be conservative in N fertiliser applications at planting, and allow the canola to utilise residual N during early establishment. An inverse relationship between N availability and winter survival could be due to a complex set of biochemical, shoot morphological, i.e. raised shoot meristems above the ground, and growth-induced water stress (Reese 2015). Winter canola exhibits deep rooting depths to 180 cm, and subsoil N and water access and recovery is critically important (Hocking et al. 2002; Reese 2015). Furthermore, iPNW climate change projections of hotter, drier summer months (Abatzoglou et al. 2015) portend a need for enhancing deep, strong-rooted winter crops such as canola for adapting to foreseen climate change (Hatfield et al. 2001; Blum 2009; Lynch 2015).

These climate change forecast models predict 5–15% increases in iPNW regional annual precipitation, but with increasing proportions occurring during the winter and spring months with drier, hotter summers. This trend will necessitate improvements in water and N infiltration and subsoil storage during winter months for later access during active crop development. Canola also has a reputation as a strong taprooted crop capable of creating macro biopore channels for facilitating saturated water flow and root pathways for subsequent crops. Yet canola roots cannot always penetrate soil horizons with high physical and chemical impedance (Cresswell and Kirkegaard 1995; Watt et al. 2006). Tillage pans and genetic soil horizons in the iPNW have been observed to impede canola roots, causing characteristic ‘J’ hooking of the taproot, forcing it to turn 90 degrees along the plan of the soil pan, until it encounters a crack where it can continue vertical development (Lisson et al. 2007). This may be a plausible explanation for new canola grower testimonials claiming rotational benefits are not seen until a second or third rotation.

Irrigated crop zone

Rotational fit. The irrigated temperate desert of central Washington and Oregon supports perennial tree and vine fruit production as well as 500 000 ha of many high value agronomic crops such as potato and sweet corn, where small grain cereals are used as a rotational crop, and winter wheat is only ~8% of the area (Table 1, Fig. 1). As many high value crops, for example potato, sweet corn, onion, beans are grown in this zone, a much lower adoption is projected for this zone, with canola mostly restricted as a substitution for wheat in the irrigated rotations of central Washington and Oregon.

In addition, with opportunities to follow early harvested fresh vegetable crops, dual purpose use of canola has potential to diversify and intensify irrigated rotations similar to dryland applications (Neely 2010; Walsh 2012; Lilley et al. 2015). In this zone of extended growing degree-days, double cropping under irrigation where biennial canola could bridge two short-season summer crops to yield three harvests over two growing seasons, such as Year 1: fresh peas/canola forage – Year 2: canola grain (Kincaid et al. 2011). Current efforts are focussed on production of silage from first-season canola vegetation in central Washington. Comparable canola grain yields of 2300 kg ha⁻¹ were harvested with and without forage cutting and removal (Desti et al. 2013). Yield gaps between predicted and observed yields may relate to J-hooking that has been observed under irrigation, similar to dryland root observations described above.

Plant establishment. As water is not a limitation under irrigation, germination and seedling establishment is not as much of an issue in this zone. For example, winter rapeseed and mustard were rapidly established in late August and early September in the south and north Columbia basin under irrigation, and substantial biomass and N accumulation occurs before the first hard frost, and under these conditions, deep soil N use should still be accounted for in oilseed rotational N fertiliser recommendations (Weinert et al. 2002). Even under irrigation, N fertiliser responses in winter canola can be minimal, due to build up of residual soil N in highly fertilised rotations (Davenport et al. 2010). Even with ample water and N, winter kill is still a problem in this zone, as demonstrated in an irrigated winter wheat, spring barley, winter canola rotation, where green-bridged Rhizoctonia solani on spring barley residues was suspected to infect winter canola roots, perhaps contributing to winter kill in 4 of 5 years (Paulitz et al. 2010; Schilliger et al. 2010b). Rhizoctonia solani anastomosis group 2–1 has recently been identified to infect wheat and rape roots (Sturrock et al. 2015).

Summary and future projections

Canola area has historically constituted less than 1% of the iPNW. Advancements in the development of both winter and spring cultivars have afforded flexible options in weed control management. Competitive hybrid cultivars are now commercially available with and without herbicide tolerance or resistance. Current efforts are to identify and integrate cultivars that can be successfully established, survive winter and use subsoil water and N efficiently in each of the zones. Establishment of a local oilseed processing industry, increasing global and regional canola markets for food, fuel and feed, agronomic benefits in increasing rotational diversity, and continued vigorous research and extension efforts have stimulated a recent increase in canola integration into existing monoculture wheat production in the iPNW. Modest canola rotational integration projected for each zone would achieve production goals to match current and future regional oilseed processing capacity with 300 000 canola ha per year.
An upper agronomic limit of roughly 1:1 wheat:canola has been reached in the semi-arid wheat-producing region of western Canada. Similar crop production ratios in the iPNW would approach 700,000 ha. Winter canola integration into the wheat–fallow, annual crop–transition, and irrigated cropping zones, and spring canola integration into annual cropping and transition zones will improve weed control and wheat yields, particularly with herbicide-resistant cultivars. The most critical challenges in the adaptation of canola into iPNW wheat-cropping systems include improved consistency of winter canola establishment and winter survival in the low and intermediate precipitation zones. Seeding depth and timing are critical determinants of winter and spring canola yield potential. Relevant genetic research is currently focussed on increasing seed size and hypocotyl lengths for improved seedling emergence, and on the identification of freeze-tolerant cultivars. Integration of spring canola into higher precipitation annual cropping systems requires research on innovative early planting strategies and new earlier maturing cultivars to avoid high temperature and moisture stress. Taproot architecture of canola dictates changes in standard N placement and timing strategies that have been practiced for iPNW wheat production, but the deep rooting habit of canola will contribute to efficient water and N recovery of the cropping systems. Farm enterprise economics that account for rotational benefits and production risk will help growers account for multi-year investments in canola–wheat rotations to assess the benefits of integrated canola–wheat systems.

References


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