Review

An Overview of Crop and Crop Residue Management Impacts on Crop Water Use and Runoff in the Canadian Prairies

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Abstract: Although crop and crop residue management practices are mainly used for increasing crop yield, they and the resulting changes in crop growth affect one or more hydrological components, including runoff. Based on published research in the Canadian Prairies, this paper reviews the effects of crop type, quantity of crops and crop residues, crop variability within landscapes, tillage, and stubble management practices on crop water use (termed including evaporation, transpiration and interception), snow trapping, and water infiltration, with the aim to discuss major impacts of crop and residue management on runoff. Rainfall runoff is influenced by rain interception and crop water use, and it can be reduced by choosing appropriate crop types, increasing above-ground biomass, or increasing coverage on the soil surface, activities which coincide with the farmer's efforts of increasing crop productivity. However, although high stubble and reduced tillage for maintaining good residue cover help conserve soil moisture and improve soil health, they increase snowmelt runoff potential. The review emphasizes the need of future research to assess the agronomic and environmental trade-offs of crop residue management, the linkage between crop water use and runoff, and the impacts of crop and residue management on runoff across various temporal and spatial scales.

Keywords: crop management; crop residue management; crop water use; evaporation; interception; landscape variability; runoff; snow trapping; snow sublimation; transpiration

1. Introduction

Dry and cold regions play a key role in producing small grains and oilseeds of the world. In Canada, about 85% of the national field-crop area, 95% of total wheat (*Triticum aestivum* L.) and almost all canola (*Brassica napus* L.) production is found in the Prairie provinces of Saskatchewan, Alberta and Manitoba [1]. In the agricultural region of the Canadian Prairies, where semi-arid and sub-humid continental climates dominate, crop production is constrained by water availability. Due to the dry climates, runoff volumes generated in this region are low, as compared to more humid regions which, at the edges of fields, usually accounts for less than 20% of annual precipitation in 80% of years [2]. However, runoff has important water quality implications, as phosphorus concentrations in runoff [3] often exceeds the threshold value for causing eutrophication in lakes and rivers [4]. Agronomic water deficiency and environmental nutrient runoff constitute the co-existing challenges for water management in the Prairies.

Canadian farmers strive to improve agronomic production. While the total cropland area has remained rather stable since 1970s, crop yield per unit area has almost doubled. In Saskatchewan, Manitoba and Alberta, average wheat yield increased from 1740, 1770 and 1870 kg ha^{-1} year^{-1} in 1970–1979 to 2740, 3410 and 3440 kg ha^{-1} year^{-1}, respectively [5]. Meanwhile, average canola yield increased from 1080, 1100 and 1040 kg ha^{-1} year^{-1} to 1990, 2070 and 2230 kg ha^{-1} year^{-1}, respectively [5]. The increase in crop yield is

largely due to improved crop breeding and farming practices, including crop and crop residue management. Although many of the practices related to crop and crop residue management, such as crop rotation, stubble management and conservation tillage, are mainly used in order to improve soil and crop productivity, these practices also impact various hydrological processes, i.e., rain interception, transpiration, evaporation, snow trapping, water infiltration, and runoff.

The impact of crop and crop residue management on the hydrological cycle and runoff can be considerable, as differing management practices influence the hydrological processes in different ways and/or to different extents. The relevant past field research in the Canadian Prairies has mostly focused on understanding management impacts on soil water availability and crop production [6–15], with limited direct linkage to snowmelt [16–19] or rainfall runoff [3,17,20–22]. Still, there is a lack of synthesized information to elucidate the crop and residue management impacts in the contexts of the hydrological cycle and runoff.

In this paper, we review how crop and crop residue management (i.e., type, quantity and coverage of crops and residues, tillage, etc.) affect the hydrological processes of evapotranspiration, interception, snow trapping, water infiltration and runoff in the Canadian Prairies, and attempt to use the findings of the literature to assess the potential direct and indirect impacts of management on runoff. The papers used in the review were collected from the Web of Science database and based on expert knowledge of the relevant research conducted in the Canadian Prairies. A summary of papers by topics reviewed is given in Table A1. Given the overall lack of research directly addressing the crop–hydrology relationship, the review aims to identify some of the related knowledge gaps and research needs for developing field-level options for managing runoff.

2. An Overview of How Crops and Crop Residues Affect the Hydrological Cycle

In the Canadian Prairies, both rainfall and snowfall derive runoff, and runoff generation can be affected by growing crops and crop residues through their involvement in the processes of interception, transpiration, evaporation, snow trapping, melt and sublimation, and water infiltration (Figure 1). Interception describes the stopping of rain and snow by crop canopy or crop residue from reaching the ground. This water is lost to the atmosphere through evaporation or sublimation. Transpiration describes the movement of water within a plant and the subsequent loss of water as vapor from the plant through stomata. Evaporation describes the loss of soil water to the atmosphere from the soil surface, and of interception water from surface of the crop canopy and residue. Interception, transpiration and evaporation are hard to separate in field experiments, and they are often lumped and simply referred to as evapotranspiration when being measured with the commonly used methods, such as eddy covariance and water balance [23]. Snow trapping describes the capture of snow by the above-ground part of a plant, melt describes the process of snow becoming liquefied due to heat, and sublimation describes the loss of snow by changing into water vapor in the air without first melting into water. Infiltration describes the process by which water on the soil surface enters the soil.

When rainfall occurs, part of the water is intercepted by growing crops and/or crop residues and subsequently evaporated to the air, and the rest of water reaches on the ground via throughfall and stemflow [24]. Along with depressional storage, which is impacted by soil surface roughness and tillage [25], and water infiltration, which is impacted by both soil and root characteristics [26], rain interception significantly affects the availability of water for runoff during a rainfall event. During the growing season, crops consume soil water, leading to water loss from the soil-plant system by transpiration. This is contrasting to evaporative water loss directly from the soil when a growing crop is absent. Evapotranspiration affects soil water storage [23], or the so-called antecedent soil moisture condition, which plays an important role in generating runoff from subsequent rainfall events [27]. During the non-growing season, when most of the snowfall occurs, crop stubble traps snow [9], and affects the snow melt process and sublimation by influencing microclimates [28,29]. Moreover, stubble management by tillage not only affects the

amount of residue left on the soil surface for snow trapping and the roughness of soil surface for depression storage over the short term, but also affects soil organic matter content and structural stability and eventually soil water infiltration capacity over the long term [30]. Consequently, crop residue management affects both the availability of melt water and antecedent soil moisture conditions for runoff. Given the hydrological processes that growing crops and crop residues are involved in, crop management during the growing season and crop residue management during the non-growing season both have a potential to impact runoff. Potentially, the impacts are affected by management practices that influence the type, quantity and coverage of growing crops and crop residues.
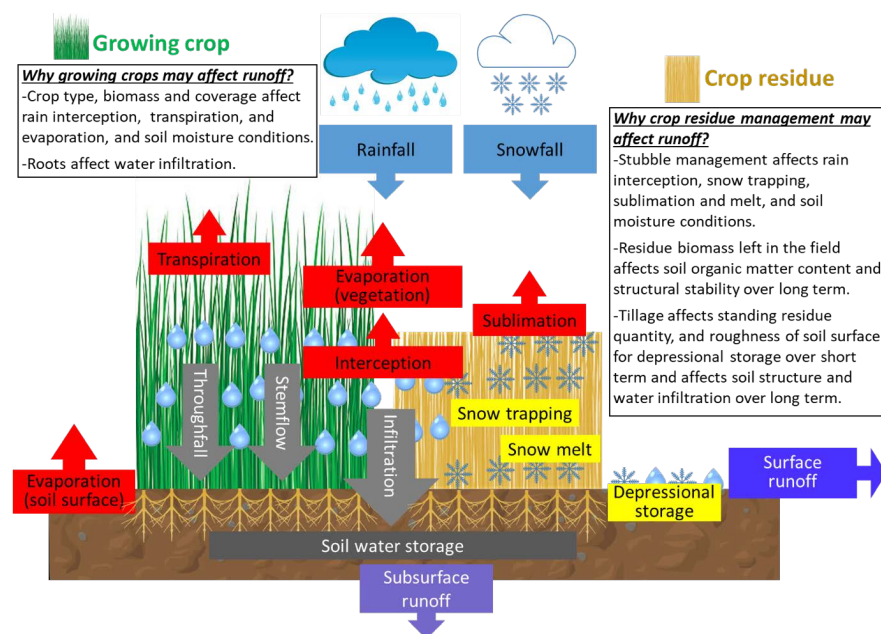
Figure 1. A diagram of the water cycle and how management of growing crops and crop residues affects runoff in the Canadian Prairies, where both snowfall and rainfall derive runoff, and surface runoff overwhelms subsurface runoff. In field research, interception, transpiration and evaporation are often measured together and simply defined as evapotranspiration.

3. Impacts of Crop Type and Biomass on Crop Water Use (Evapotranspiration)

Farmers choose crops based on agronomic and economic considerations, with very rare considerations of environmental impacts, such as runoff and nutrient transport. In the Canadian Prairies, crop production is widely limited by soil moisture, and thus agronomic water research has been largely focused on understanding crop water demand and crop water use. Crop water demand is the amount of water that a particular crop can use given an unlimited supply of water, which is the potential of water use based on the crop type, climate and soil conditions. Crop water use is the actual amount of water used by a crop for growth and cooling. It is alternatively called evapotranspiration, and is usually estimated as the difference between soil moisture at seeding and soil moisture at harvest, plus precipitation during the growing season [8,11]. Thus, it is a lumped estimation of interception, transpiration and evaporation.

Previous agronomy research in the Canadian Prairies showed that both crop water demand and crop water use varied widely by region and year, as a result of climate variability [8,10–12,14,15,31]. Even so, certain crops tend to use more water than others (Table 1). In southwestern Manitoba, for example, Martel et al. [15] observed that crop water use followed: soybean (*Glycine max* L., 400 mm) > fall rye (*Avena sativa* L., 370 mm) > canola (350 mm) = spring wheat (350 mm) > proso millet (*Panicum miliaceum* L., 240 mm). In west-central Saskatchewan, crop water use was estimated as 450 mm for alfalfa (*Medicago sativa* L.), 400 mm for canola, 350 mm for wheat and fall rye, and 300 mm

for barley (*Hordeum vulgare* L.) [32]. The differing amounts of water use by different crop types have important implications on runoff, as they affect water balance in the soil. It is anticipated that the more water a crop uses, the less water contributes to runoff. Moreover, crop water use also affects antecedent soil moisture conditions for runoff events: drier soils lead to lower likelihood of runoff generation [27]. Currently, however, there is a general lack of research data that directly relates the agronomic crop water use to runoff implications.

Table 1. Summary of rain interception storage capacity, rain interception loss, and evapotranspiration by different types of crop canopy and residue.

Category	Crop Water Demand (mm)	Actual Evapo-Transpiration (mm)	Rain Interception Storage Capacity (mm)	Rain Interception Loss (%)
Crop canopy				
Spring wheat (*Triticum aestivum* L.)	275–325 [31]	174–485 [8,11,15]	2.1 [33]	10–36 [34,35]
Barley (*Hordeum vulgare* L.)	n.a.	250–350 [32]	1.9 [33]	n.a.
Oat (*Avena sativa* L.)	n.a.	n.a.	3.0 [33]	7–58 [34–36]
Fall rye (*Secale cereal* L.)	n.a.	140–370 [10]	1.2 [37]	4–6 [34]
Corn (*Zea mays* L.)	375–450 [31]	300–400 [32]	3.2 [33] [1]	16–22 [35,36]
Canola (*Brassica napus* L.)	n.a.	260–450 [12,14]	n.a.	56 [38]
Soybean (*Glycine max* L.)	n.a.	400 [15]	n.a.	15–35 [35,36]
Annual ryegrass (*Lolium multiflorum* L.)	n.a.	n.a.	2.8 [39]	n.a.
Alfalfa (*Medicago sativa* L.)	400–450 [31]	400–500 [32]	n.a.	n.a.
Clover (*Trifolium spp.* L.)	n.a.	n.a.	3.1 [40]	n.a.
Crop residue				
Wheat (*Triticum aestivum* L.)	n.a.	n.a.	1.1–2.4 [41] [†]	n.a.
Corn (*Zea mays* L.)	n.a.	n.a.	0.7–1.7 [41] [†]	n.a.
Soybean (*Glycine max* L.)	n.a.	n.a.	0.7–1.8 [41] [†]	n.a.

[1] Average for multiple plant densities; [†] Each value is an average of two rainfall intensities, and the range is for 2–6 Mg residue ha^{-1}. n.a.: value not available or not applicable.
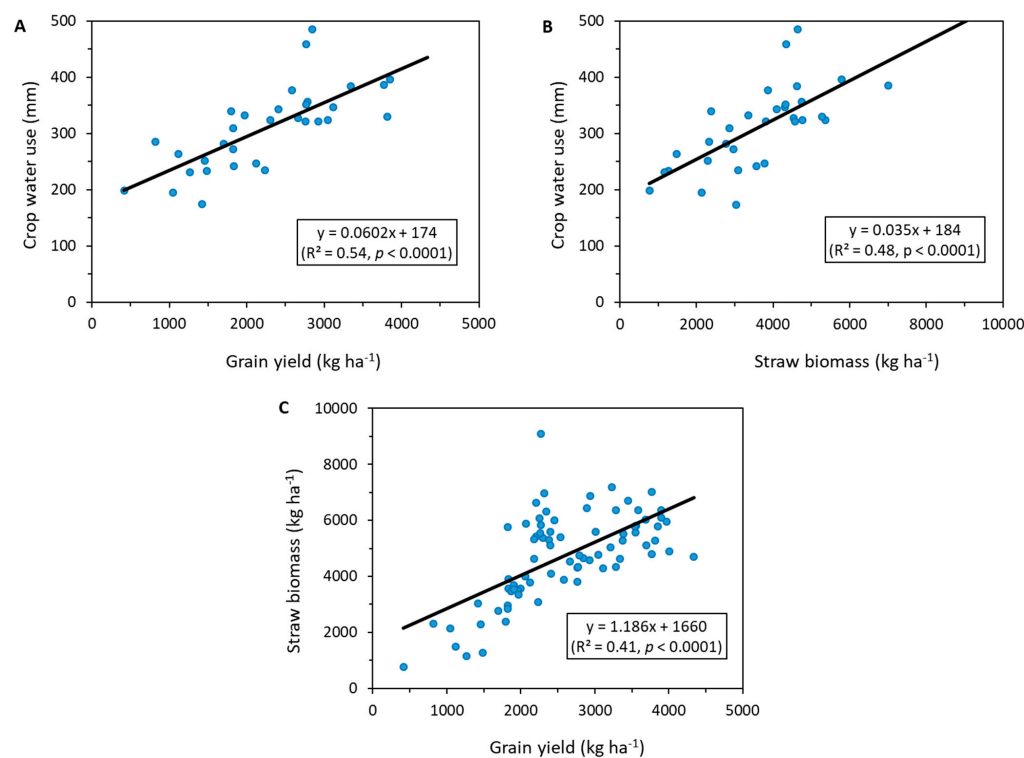
Figure 2. Relationships between growing season crop water use and grain yield (**A**, *n* = 32), between growing season crop water use and straw biomass (**B**, *n* = 32), and between crop straw biomass and grain yield (**C**, *n* = 78), all for spring wheat. The data were obtained from published work in the Canadian Prairies: [8,11] for (**A,B**), and [8,11,42–44] for (**C**). Each data point represents a site-year field experiment.

A quantitative analysis based on published data [8,11] shows that growing season crop water use of spring wheat significantly increases with increasing grain yield (Figure 2A) and increasing straw biomass (Figure 2B). This suggests that there is large potential to increase crop water use and thus reduce runoff volume by increasing crop production. As straw biomass is positively correlated to grain yield (Figure 2C), grain yield can be used as an indicator of the overall production of the above-ground biomass, and a predictor of water use by the crop. The analyses here and above suggest that runoff can be reduced by increasing crops' use of water (including both transpiration and interception), which can be achieved by choosing appropriate crop types and/or increasing crop production.

Impacts of Crop Type and Biomass on Rain Interception

In the Canadian Prairies, rain interception by crops has not been explicitly studied as an individual hydrological component. However, studies outside the Prairies have shown that different types of crops have differing rain interception storage capacities and rain interception losses by canopy (Table 1). For example, Lull [35] reported that wheat (36%), corn (*Zea mays* L., 16%), and soybean (15%) had much greater rain interception loss than rye (7%). This indicates that rain interception alone may play a critical role in affecting runoff volume. Notably, the rain interception losses reported in the literature ranged widely even for the same crop used in different studies (Table 1), which is probably due to varying canopy parameters and rainfall characteristics among the studies. The quantity of crop canopy appears to be a key factor influencing rain interception, as rain interception storage capacity is found to be related to the weight of canopy [45] and the leaf area index [33]. Moreover, crop residues also have considerably high rain interception storage capacity, which, similarly to that of crop canopy, varies by type and quantity of the residue [41] (Table 1). Rain interception by vegetation was found to significantly affect hydrological effective rain, which is the portion of rain that arrives on the soil surface during a rainfall event, and affects runoff hydrology in forests [46]. Similarly, it may have a profound impact on runoff from arable land, which should be further evaluated by using the crop, soil and weather data representative of the Canadian Prairies. In addition, the impact may vary from region to region, and thus needs to be evaluated through a rigorous cross-region assessment.

4. Impacts of Crop Residue Management on Snow Trapping, Sublimation and Melt

Crop residue management affects various snow processes, including snow trapping, sublimation and melt. To address the crop production challenge associated with the low precipitation during the growing season, the Prairie farmers have developed measures to conserve snow water, using snow ridging [47], row crops or summer-fallow substitutes [48], and maintenance of stubble [49]. Maintaining higher and/or more crop stubble has been found to be more effective in trapping snow than shorter and/or less stubble (Table 2). Several studies have shown greater amounts of snow trapping in the presence of a perennial crops or crop stubble than in summer fallow [6,7,16]. For example, a 15-year field study in Saskatchewan showed that standing wheat stubble on average conserved almost 60 mm water over fall and winter as compared to only 10 mm conserved by bare soil/land fallow [6]. Moreover, another 10-year study from Saskatchewan showed that tall wheat stubble trapped on average about 70 mm snow water equivalent as compared to 40 mm by short stubble [9].

Crop residue management is often associated with tillage operations, which have varying impacts on snow trapping. In both Manitoba and Saskatchewan, conservation tillage and zero-till (direct-seeding or no-till), which maintained substantially more crop residues on the soil surface, were found to trap more snow than conventional tillage that incorporated most of the residues into the soil [17,19]. In Alberta, confounding findings were reported. While Maule and Chanasyk [7] found that zero-till and chisel plows trapped significantly more snow than disc plows, Puurveen et al. [16] reported even a greater amount of snow trapping by conventional tillage than conservation tillage. The

trend in Puurveen et al. [16] may be due to the fact that conventional tillage can increase the roughness of soil surface and somewhat help to trap snow. The greater amounts of snow trapped due to higher and/or more crop stubble remaining on the soil surface or increasing surface roughness can increase snowmelt runoff in spring.

Table 2. Snow trapping (snow water equivalent, mm) as affected by different types of crops and crop residue management practices.

Experimental Location	Summer Fallow	Perennial Crop	Annual Crop						
			Type	Conservation or Zero Tillage	Short Stubble	High Stubble	Conventional Tillage	Chisel Plow	Disc Plow
La Glace, AB [16]	67 ‡	82 ‡	Barley, canola	79 ‡	n.a.	n.a.	83 ‡	n.a.	n.a.
Edmonton, AB [7]	8 #	n.a.	Barley	23 #	n.a.	n.a.	n.a.	24 #	13 #
Scott, SK [6]	10 ‡	n.a.	Wheat	59 ‡	n.a.	n.a.	n.a.	n.a.	n.a.
Swift Current, SK [9]	n.a.	n.a.	Wheat	n.a.	38 ‡	68 ‡	n.a.	n.a.	n.a.
Swift Current, SK [19]	n.a.	n.a.	Green manure	44 ‡	n.a.	n.a.	30 ‡	n.a.	n.a.
Southeastern SK [13]	n.a.	6 #	Wheat	8 #	n.a.	n.a.	n.a.	n.a.	n.a.
Miami, MB [17]	n.a.	n.a.	Cereals, canola	65 ‡	n.a.	n.a.	53 ‡	n.a.	n.a.

‡ Average of multiple years. # Average for multiple times or locations of measurements within a year. Tillage refers to the previous fall. n.a.: value not available or not applicable.

In addition to affecting snow trapping, residue management also influences snow transport and sublimation losses (Table 3), by influencing microclimates. Compared to bare soil, standing stubble decreases wind speed near the soil surface [12], delays the initiation of blowing snow, and decreases sublimation losses and the transport of snow [28]. Moreover, stubble expedites snowmelt by intercepting and absorbing more solar radiation than snow, by conducting heat and by reflecting energy to the snowpack [50,51]. Both snow and crop residue have high albedos and they have insolation capacity, which can slow the warming and drying of the soil and indirectly increase soil moisture content. All these effects indicate that the presence of stubble expedites snowmelt generation as compared to bare soil. However, one exception may exist in stubble burning, which removes crop residues and leaves black ash on the soil surface. After stubble burning, the soil has very low albedo, which potentially increases the interception and absorption of solar radiation and expedites the generation of snowmelt. Stubble is often burned as a crop residue management practice in the Red River Valley of Manitoba [52], however, research is lacking to assess its impacts on the water cycle and runoff.

Table 3. Snow balance in fallow and stubble fields of 1 km length in Saskatchewan (adapted from [53,54]). The components of snow balance include snowfall in snow water equivalent, and blowing snow transport loss, sublimation loss and snow accumulation as percentages of snowfall.

Site (Winter Temperature and Wind Speed)	Land Cover	Snowfall (mm)	Transport (%)	Sublimation (%)	Accumulation (%)
Prince Albert (−11.6 °C, 4.5 m/s)	Fallow	103	13	27	60
	Stubble	103	9	23	68
Yorkton (−10.6 °C, 4.7 m/s)	Fallow	125	13	23	64
	Stubble	125	8	15	77
Regina (−8.9 °C, 6.0 m/s)	Fallow	113	36	41	23
	Stubble	113	19	34	48
Swift Current (−6.7 °C, 6.6 m/s)	Fallow	132	29	29	42
	Stubble	132	11	22	67

5. Impacts of Crop and Residue Management on Water Infiltration

Crop and residue management affect water infiltration, which is a key driver of surface runoff. By intercepting rainfall and reducing raindrop impact, crop and crop residue reduce soil crust formation [55]. Also, roots enhance water infiltration by creating macropores

and stabilizing soil aggregates [56]. Moreover, the amount of crop residue that is returned to the soil affects soil organic matter content, soil structure and infiltration over the long term [57]. Quantities of roots and crop residue, and their consequent effects on the soil increase with increasing crop yield. Given that different types of crops have different rain interception capacities, rooting systems and quantities of residues, they are expected to affect infiltration by varying extents. Gray et al. [58] reported that infiltration rate followed: good pasture > small grains > poor pasture > row crop > bare soil. However, Pikul et al. [59] found greater infiltration rates in fallow than in lentils, which indicates that crop impact on water infiltration is also affected by factors other than the crop itself, including soil and rainfall characteristics.

Tillage affects water infiltration by influencing soil surface roughness, soil bulk density and porosity in the short term, and organic matter content and aggregate stability in the long term. Studies have found that long-term conservation tillage or zero-till helps increase soil organic matter content, improve soil structure and aggregate stability, developing stable and continuous pores and thus increasing water infiltration [60–62]. In the short term, however, zero-tillage may have undesirable effects on infiltration. Singh et al. [63] found that zero-tillage increased bulk density and penetration resistance in both a Black Chernozem and a Gray Luvisol in Alberta as compared to tillage, and that zero-tillage reduced the infiltration rate in the Black Chernozem (not in the Gray Luvisol). In contrast, tillage creates increased soil surface roughness that increases water detention and infiltration.

6. Impacts of Crop and Residue Management on Runoff

Given the aforementioned crop and residue effects on rain interception, transpiration, evaporation, snow trapping and water infiltration, using a particular crop or crop rotation method over others is expected to have a different impact on runoff. Table 4 summarizes a collection of published work that has evaluated the impacts of crop and residue management on runoff in the Canadian Prairies. Indeed, the findings show varying impacts by different crops and management practices.

For rainfall runoff, a forage crop was shown to reduce runoff as compared to fallow or an annual crop in most cases [2,20,21]. In few cases, forage had similar runoff volume to an annual crop [20]. The reduction in runoff by forage is likely associated with its denser coverage on the soil surface and longer growing season than other crops, which increases rain interception and transpiration. Although summer fallow is widely believed to increase rainfall runoff as compared to annual crops, comparisons between summer fallow and other crops have shown inconsistent patterns. Fallow was found to generate more runoff than barley in Alberta [20], but it had lower runoff volume than wheat and corn in most of the site-years evaluated in Manitoba [21]. The different patterns may be due to differing weather conditions and soil properties of the studies, which need to be further evaluated. With regard to crop types, corn appeared to consistently generate more runoff than wheat [21]. Native grass and Russian wild rye were found to reduce runoff by more than 50% as compared to wheat and crested wheatgrass [64]. In addition to crop type, other management practices can also affect runoff. Growing barley in rows perpendicular to a slope was found to reduce runoff more than the rows parallel to the slope [20]. Light grazing, which keeps more crop biomass in the field, reduced runoff as compared to heavy grazing [22]. Overall, the findings point to the importance of maintaining crop biomass to reduce rainfall runoff.

For snowmelt runoff, on the contrary, perennial forages generally increase runoff volume as compared to annual crops [16,18], as their denser coverage on the soil surface and prolonged growing season help trap more snow over winter. Moreover, conservation tillage and zero-till were found to significantly increase snowmelt runoff and conventional tillage [17,19]. Similarly, light grazing increased snowmelt runoff more than heavy grazing [22].

Table 4. Rain or snow water equivalent (SWE), and runoff volume (all in mm) as affected by different crop types and residue management practices in the Canadian Prairies. Values of medians or averages (when medians are not available) are given, with ranges in parentheses. A-crop: annual crops; C-wheatgrass: crested wheatgrass; P-forage: perennial forages; R-wildrye: Russian wild rye; S-bromegrass: smooth bromegrass; F.: fallow; G.: grazing; CV-Till: conventional tillage; CS-Till: conservation tillage; ZR-till: zero tillage.

Experimental Location and Year	Rain or SWE	Runoff Volume as Affected by Different Treatments					
		Rainfall runoff					
Lethbridge, AB 1985–1987 [20] a	168 (142–194)[1]	F. 28 (13–43)[1]	Barley-S 17 (11–23)[1]	Barley-C 8 (7–8)[1]	Forage 9 (7–10)[1]		
Lethbridge, AB 2006 [64] b	53	Native grass 9	C-wheatgrass 20	R-wildrye 7	Wheat 28		
Keephills, AB 1995–1997 [55] c	53	F. hay field 25 (23–25)‡	Hayed hay 18 (10–23)‡	Mowed hay 24 (12–25)‡	F. pasture 25 (23–26)‡	G. pasture 27 (24–29)‡	
Lacombe, AB 1994–1995 [22] d	429 (335–523)[1]	Barley/triticale 5 (4–6)[1]	Triticale 2 (1–2)[1]	S-bromegrass 1 (<1–3)[1]	Light G. <1 (<1–1)[1]	Medium G. 3 (2–3)[1]	Heavy G. 5
Miami, MB 1988–1990 [21]	182 (100–331)[1]	F. 9 (5–112)[1]	Wheat, CV-till 16 (11–128)[1]	Corn 18 (5–240)[1]	Alfalfa 2 (0–7)[1]		
Roseisle, MB 1988–1990 [21]	138 (101–292)[1]	F. 25 (7–94)[1]	Wheat, CV-till 8 (2–157)[1]	Corn 12 (8–73)[1]	Alfalfa 2 (0–5)[1]		
Boissevain, MB 1988–1990 [21]	161 (87–238)[1]	F. 13 (6–26)[1]	Wheat, CV-till 15 (4–49)[1]	Corn 21 (8–53)[1]	Alfalfa 1 (0–1)[1]	Wheat, CV-till 16 (4–40)[1]	
Brandon, MB 1988&1990 [21]	279 (269–288)[1]	F. 36 (10–61)[1]	Wheat, CV-till 36 (19–54)[1]	Corn 47 (26–68)[1]	Alfalfa 12 (3–20)[1]	Wheat, CV-till 31 (16–46)[1]	
Mami, MB 2007–2009 [3]	431 (231–535)[1]	A-crop 5 (1–11)[1]	P-forage 0				
Miami, MB 1997–2007 [17]	363 (63–507)[1]	A-crop, CS-till 6 (0–30)[1]	A-crop, CV-till 14 (0–59)[1]				
		Snowmelt runoff					
La Glace, AB 1985–1986 [16]	80 (67–92)[1]	F. 52 (41–62)[1]	Barley, till 75 (58–92)[1]	Barley, stubble 70 (61–79)[1]	Forage 77 (67–87)[1]	Canola, till 62 (56–68)[1]	Canola, stubble 65 (60–70)[1]
Lacombe, AB 1993–1996 [22] d	73 (49–97)[1]	Barley/triticale 60 (26–94)[1]	Triticale 52 (11–93)[1]	S-bromegrass 60 (18–101)[1]	Light G. 72 (21–122)[1]	Medium G. 38 (9–67)[1]	Heavy G. 60 (21–98)[1]
Swift Current, SK 1995–2011 [19]	26 (5–109)[1]	F., ZR-till 29 (5–185)[1]	F., CV-till 4 (1–26)[1]	Wheat, ZR-till 9 (2–38)[1]	Wheat, CV-till 7 (2–30)[1]		
Miami, MB 2005–2012 [18] e	n.a.	A-crop 39	P-forage 59				
Miami, MB 1997–2007 [17]	80 (6–99)[1]	A-crop, CS-till 59 (8–96)[1]	A-crop, CV-till 45 (0–120)[1]				

[a] Simulated rainfall. Barley-S: barley sown in rows parallel to the slope; and Barley-C: sown perpendicular to the slope. [b] Simulated rainfall. The experiment was conducted at one site-year. [c] Simulated rainfall. Three sites for each of the hay treatments and two sites for each of the pasture treatments. [d] Each value for a crop is an average of three grazing treatments; and each value for a grazing treatment is an average of four crops. [e] Each value is an average of multiple years. [1] The range shows difference between years. ‡ The range shows the difference between sites.

Challenges remain when crop type and management practices are considered at a year-round level. While a greater crop cover, larger biomass, or longer growing season is preferred for increasing crop productivity and reducing rainfall runoff, it can increase unfavorable snowmelt runoff. A similar situation exists for conservation tillage and zero-till, which are beneficial for improving soil health and meeting crop water demands, but increase snowmelt runoff. In practice, it should be noted that the extent of land cover by crop residues can differ greatly among crops, even with the same tillage method. For instance, a chisel plow (twisted points) in corn and small grain fields often leaves 50–70% of residue coverage on the soil surface but only 30–40% in soybean fields [65]. The different residue coverage will have varying influences on rain interception, snow trapping, and runoff. Due to the differences in crop water use and land coverage, crop rotations (e.g., typical corn-soybean versus wheat-canola) can have very different implications on total runoff. Under zero-till, theoretically, a corn-soybean rotation in place of wheat-canola may increase both rainfall and snowmelt runoff, given a smaller soil coverage of corn during the growing season but a greater residue quantity for trapping snow during the non-growing season. Such impacts need to be assessed and verified through more field research.

Within a crop field, topographic and soil variability results in variability in crop growth and yield (Table 5), as well as crop residue production [66]. In hummocky moraine areas of central Saskatchewan, for example, Moulin et al. [67] found that wheat yield ranged 500–4300 kg ha^{-1} at different positions of a cultivated transect. In another glacial till landscape, Walley et al. [68] found that average spring wheat yield ranged from 1900 kg ha^{-1} in upper slope positions to 3200 kg ha^{-1} in lower slope positions. At upper slope positions,

the soil is often drier and more eroded, and has lower fertility than that at lower positions. In dry years, when soil moisture critically determines crop growth, upper slope positions commonly have lower crop yield than lower positions do [69]. In wet years, nevertheless, the trend may become the opposite because waterlogging can reduce crop yield in depressional areas [69]. Moreover, crop variability within landscapes can result from soil conditions that affect crop growth, such as pH, salinity, compaction, management, and other factors such as pests [70]. It should be noted that soil erosion is a major cause of the observed variability in soil and crop properties within fields at this scale [66]. The crop variability within fields and watersheds can play a critical role in influencing soil hydrology, nutrient uptake, and water and nutrient losses at different landscape locations, which require a place-based management approach for soil and water conservation. However, research related to examining the hydrological and environmental effects of such variability and addressing place-based management is generally lacking in the literature.

Table 5. Examples of wheat grain yield variability within landscapes in Saskatchewan.

Site	Year	Landscape Position	Yield (kg ha^{-1})
Hepburn [68]	Three-year average	Upper slope	1910
		Mid-slope	2760
		Lower slope	3160
Alvena [69]	Dry year	Knoll	710
		Back slope	1240
		Front slope	1270
		Depression	2230
	Wet year	Knoll	3000
		Back slope	2380
		Front slope	3120
		Depression	1960

7. Implications in Changing Management, Crop Productivity and Climate

Although it has not been well assessed, crop impacts on runoff have likely changed over time, as a result of changing crop production system and climate. Indeed, crop production in the Canadian Prairies has experienced dramatic changes in management and productivity during the last several decades. When Manitoba, Saskatchewan and Alberta are considered together, the percentage of seeded cropland that was managed as conservation tillage or zero-till increased from 0% in 1971 to 87% in 2016 (Table 6).

Land area for summer fallow decreased sharply from about 15 million ha in 1970 to 0.6 million ha in 2019 (Figure 3A), while wheat seeding area peaked around 1990 (Figure 3B), and seeding areas of canola (Figure 3C), corn (Figure 3D) and soybean (Figure 3E) dramatically increased from 1970s to 2010s. During the same time span, notably, yields of wheat (Figure 3B), canola (Figure 3C) and corn silage (Figure 3D) about doubled. Moreover, there is a tendency of increasing land area for pulse crops (e.g., lentils and dry peas; Table A2), and increasing land area for corn–soybean rotation in place of traditional cereal-canola rotation in certain areas, such as the Red River Valley in southern Manitoba. The trend of tame hay production was different from that of grain crops. While the seeding area of tame hay peaked around 2005, its yield was generally stable during 1970–1991, decreased during 1992–2002, and increased during 2003–2019 (Figure 3F).
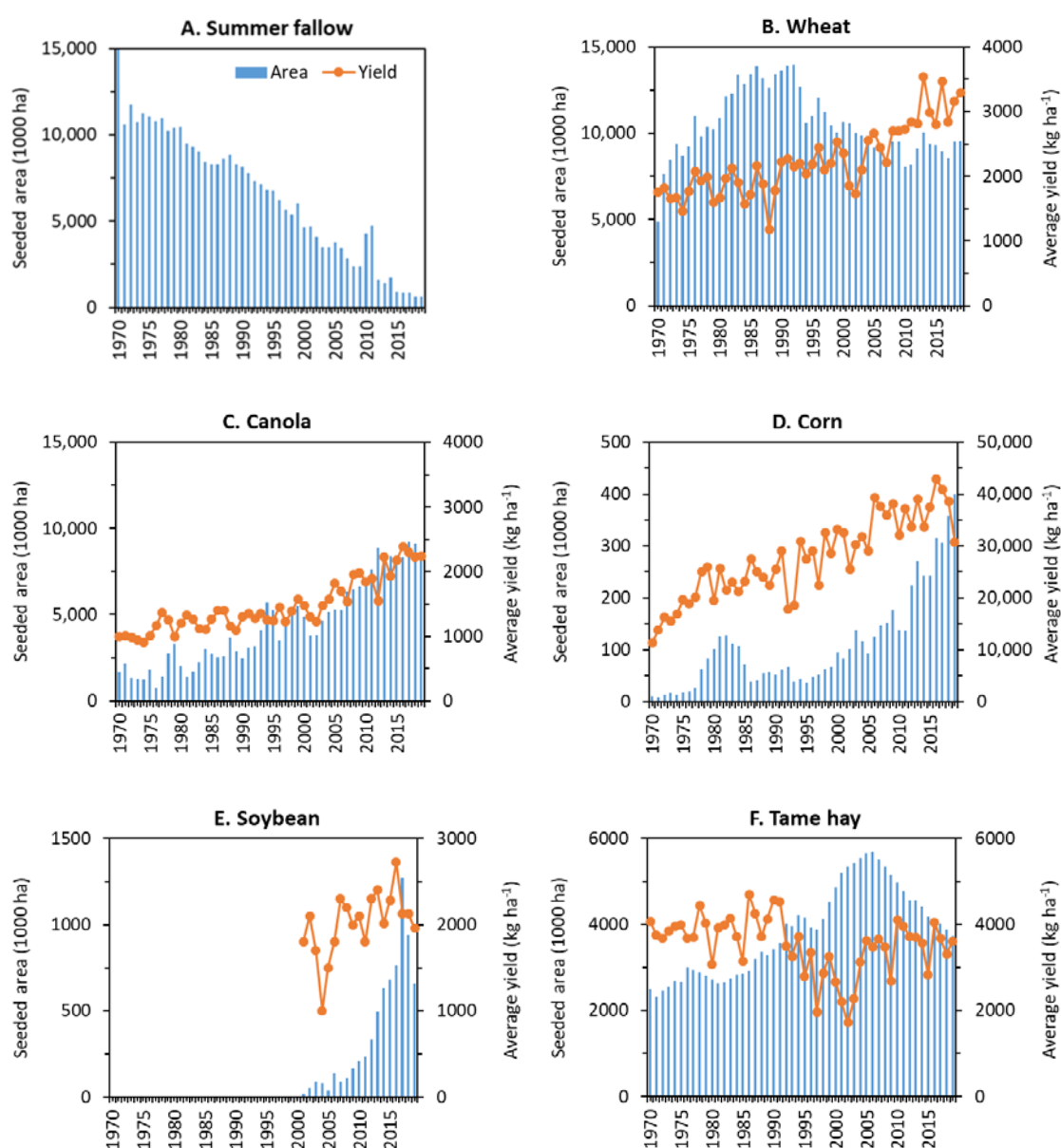
Figure 3. Total seeded area and average yield for major field crops in the Canadian Prairie provinces of Manitoba, Saskatchewan and Alberta from 1970 to 2019 (data source: Statistics Canada [5]). Wheat includes winter wheat, spring wheat and durum. Corn seeding area is the sum of areas for both corn grain and corn silage, while only the yield of corn silage is presented in the figure.

All the changes are expected to have affected runoff at the field, watershed and regional scales over the long term, providing the profound impacts of tillage, land cover, crop and residue type, and biomass on snow trapping, rain interception, evaporation, transpiration, and water infiltration as discussed in the sections above. There is a growing interest among Prairie farmers in using cover crops to improve soil health, which was considered unfeasible in the past due to their poor establishment in the cold climate and consumption of soil water that was limited for the main crop. This change would need to be considered in the context of similar changes resulting from increasing land cover and crop yields.

Table 6. Summary of tillage operations in the Canadian Prairies in 1971, 1991, and 2016, showing the increasing trend of conservation tillage and zero-till.

Category	1971 [a]					1991 [b]					2016 [c]				
	AB	SK	MB	All	% [e]	AB	SK	MB	All	% [e]	AB	SK	MB	All	% [e]
Land for seeding (10³ ha)	5514	9656	2751	17,921	100	7966	13,035	4219	25,220	100	8866	15,202	4169	28,237	100
Conventional till (10³ ha) [d]	5514	9656	2751	17,921	100	5783	8334	2797	16,914	67	1028	1043	1720	3791	13
Conservation till (10³ ha) [d]	0	0	0	0	0	1934	3348	1209	6491	26	1697	2842	1612	6151	22
Zero-till (10³ ha) [d]	0	0	0	0	0	249	1353	212	1814	7	6142	11,317	837	18,296	65

[a] Total land area prepared for seeding is from Statistics Canada [5], and areas for individual tillage operations are based on Lobb et al. [71]. [b] Data are from Statistics Canada [72]. [c] Data are from Statistics Canada [73]. [d] Defined in the Census of Agriculture as: conventional tillage incorporates most of the crop residue into the soil; conservation tillage retains most of the crop residue on the soil surface; and zero tillage prior to seeding. [e] % of total land area prepared for seeding in the three provinces.

The impacts of changing management and crop productivity on runoff might have also been complicated by a changing climate. In southwest Saskatchewan, Coles et al. [74] observed a 51% increase in annual rainfall, an 18% decrease in annual snowfall, an increasing number of multi-day rain events, and increasing rain volume during the events from 1962 to 2013. During the same time period, snowmelt runoff decreased but rainfall runoff had no significant response [74]. There is a need to better evaluate historical changes in crop production, climate and runoff to make predictions for future climates and cropping systems.

8. Concluding Remarks

Through the analysis of published studies that have documented the impacts of crop and crop residue management on rain interception, evaporation, transpiration, snow trapping, water infiltration and runoff, this review demonstrates that crop and residue management have high potential to affect the hydrological cycle and runoff. The effects are influenced by farmers' selection of crop types and tillage method over the short- term, by regional trends of changing climate and cropping systems over the long term, and by factors affecting crop variability within landscapes such as topographic and soil variability. Rainfall runoff can potentially be reduced by using crops that intercept and use more water, which can be achieved by choosing appropriate crop types, increasing above-ground biomass, or increasing coverage on the soil surface. The potential reduction of rainfall runoff coincides with farmers' efforts to increase crop productivity. However, it should be noted that although high stubble and reduced tillage for maintaining good residue cover have agronomic benefits in helping conserve soil moisture and improve soil health, they increase the potential of snowmelt runoff. As snowmelt runoff often constitutes 80% of annual runoff and has important water quality implications in the Canadian Prairies [2], the agronomic and environmental trade-offs of crop residue management should be further evaluated. The review shows that there are still considerable knowledge gaps with regards to the linkage between crop water use and runoff, and the impacts of crop and residue manage on runoff across various temporal and spatial scales. The gaps should be further explored with field research and/or modelling exercises.

Appendix A

Table A1. Summary of papers reviewed for different topics.

Topics Reviewed	References
Impacts of crop type and biomass on crop water use (evapotranspiration)	Entz and Fowler [8], Gan [10], Zentner et al. [11], Cutforth et al. [12], Cardillo [14], Martel et al. [15], Nadler [31], ICDC [32]
Impacts of crop type and biomass on rain interception	Von Hoyningen-Huene [33], Horton [37], Kontorshchikov and Eremina [34], Lull [35], Baver [36], Drastig et al. [38], Merriam [39], Musgrave and Norton [40], Savabi and Stott [41], Couturier and Ripley [45]
Relationship between crop straw biomass and grain yield	Entz and Fowler [8], Zentner et al. [11], Germida and Walley [42], Wiebe et al. [43], Kubota et al. [44]
Impacts of crop residue management on snow trapping, sublimation and melt	Kirkland and Keys [6], Maule and Chanasyk [7], Campbell et al. [9], Cutforth et al. [12], Cade-Menun et al. [13], Puurveen et al. [16], Tiessen et al. [17], Schneider et al. [19], Pomeroy et al. [28,54], Harder et al. [29], Matthews [47], Champlin [48], Johnson [49], Willis et al. [50], Nicholaichuk and Gray [51], Pomeroy and Gray [53]
Impacts of crop and residue management on water infiltration	Zhang et al. [30], Burk et al. [55], Morin and Kosovsky [56], Boyle et al. [57], Gray et al. [58], Pikul et al. [59], Arshad et al. [60], Carter [61], Bedard-Haughn [62], Singh and Malhi [63]
Impacts of crop and residue management on runoff	Liu et al. [2,3,18], Puurveen et al. [16], Tiessen et al. [17], Schneider et al. [19], Beke et al. [20], Hargrave [21], Gill et al. [22], Burk et al. [55], Murphy et al. [64]
Impacts of landscape variability, and crop growth and yield	Lobb [66], Moulin et al. [67], Walley et al. [68], Chi et al. [69], Aspinall [70]

Table A2. Summary of seeded area and average yield for major field crops in Manitoba, Saskatchewan and Alberta from 1970 to 2019 (based on Statistics Canada [5]). Each value is an average for a period of every ten years.

Crop and Year Duration	Alberta		Saskatchewan		Manitoba		All Provinces	
	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})
Wheat [a]								
1970–1979	1799	1873	5990	1737	1166	1774	8955	1769
1980–1989	2905	2041	8076	1661	1820	1980	12,801	1793
1990–1999	2914	2510	7269	2090	1781	2350	11,964	2231
2000–2009	2675	2700	5597	2050	1354	2760	9626	2330
2010–2019	2837	3436	5010	2735	1210	3412	9057	3045

Table A2. *Cont.*

Crop and Year Duration	Alberta		Saskatchewan		Manitoba		All Provinces	
	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})
Barley								
1970–1979	2140	2293	1549	2173	727	2170	4416	2231
1980–1989	2359	2687	1456	2249	754	2569	4569	2528
1990–1999	2111	3140	1607	2720	518	3120	4236	2978
2000–2009	1900	3120	1771	2640	393	3260	4064	2924
2010–2019	1397	3729	990	3230	162	3559	2549	3524
Oats								
1970–1979	892	2101	824	1880	485	1820	2201	1956
1980–1989	721	2417	506	1852	245	2008	1472	2155
1990–1999	584	2490	665	2250	290	2550	1539	2398
2000–2009	513	2570	845	2370	362	2850	1720	2531
2010–2019	311	3235	598	3313	202	3488	1111	3323
Corn [b]								
1970–1979	4	7085	1	782	25	17,656	30	15,684
1980–1989	13	36,623	0	n.a.	70	16,392	83	19,561
1990–1999	8	33,916	0	n.a.	45	23,014	53	24,660
2000–2009	27	37,402	9	25,785	94	31,190	130	32,106
2010–2019	74	37,683	26	34,592	172	35,865	272	36,238
Canola								
1970–1979	714	1035	795	1079	253	1100	1762	1064
1980–1989	1046	1261	1019	1240	407	1175	2472	1238
1990–1999	1515	1360	1997	1261	795	1510	4307	1342
2000–2009	1652	1740	2522	1450	1055	1740	5229	1600
2010–2019	2572	2233	4469	1991	1314	2068	8355	2078
Soybean								
1970–1979	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1980–1989	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1990–1999	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2000–2009	n.a.	n.a.	n.a.	n.a.	88	1822	88	1822
2010–2019	5	1769	136	1717	525	2265	666	2149
Flax seed								
1970–1979	91	992	276	911	303	790	670	867
1980–1989	37	1232	214	1026	339	1020	590	1035
1990–1999	29	1400	390	1250	255	1350	674	1294
2000–2009	20	1520	519	1170	142	1290	681	1205
2010–2019	36	1892	348	1415	44	1494	428	1463
Lentils								
1970–1979	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1980–1989	3	852	82	983	14	1187	99	1008
1990–1999	11	1141	287	1331	29	1291	327	1321
2000–2009	9	1063	674	1243	6	1240	689	1241
2010–2019	103	1832	1350	1549	1	897	1454	1569
Dry peas								
1970–1979	6	1847	5	1569	20	1592	31	1638
1980–1989	14	2387	55	1606	50	1762	119	1763
1990–1999	132	2490	393	2030	67	2040	592	2134
2000–2009	260	2280	1028	1950	52	2450	1340	2033
2010–2019	552	2729	910	2349	32	2772	1494	2498
Tame hay								
1970–1979	1378	4023	786	3524	517	4231	2681	3917
1980–1989	1591	4270	760	2970	567	4011	2918	3881
1990–1999	2042	3590	1152	2708	784	3785	3978	3373
2000–2009	2528	3016	1902	2452	941	3490	5371	2899
2010–2019	1916	3997	1698	3113	695	4026	4309	3653

Table A2. *Cont.*

Crop and Year Duration	Alberta		Saskatchewan		Manitoba		All Provinces	
	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})	Area (10^3 ha)	Yield (kg ha^{-1})
Summer fallow								
1970–1979	2866	n.r.	7352	n.r.	1051	n.r.	11,269	n.r.
1980–1989	2137	n.r.	6240	n.r.	532	n.r.	8909	n.r.
1990–1999	1533	n.r.	4887	n.r.	300	n.r.	6720	n.r.
2000–2009	896	n.r.	2439	n.r.	186	n.r.	3521	n.r.
2010–2019	344	n.r.	1214	n.r.	207	n.r.	1765	n.r.

[a] Wheat includes winter wheat, spring wheat and durum. [b] Corn seeding area is the sum of areas for both corn for grain and corn for silage, while only the yield of corn for silage is presented in the table. n.a.: data not available, presumably due to their relatively small numbers in most cases. n.r.: not relevant.

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