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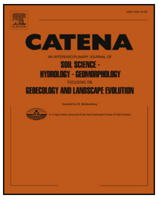

Critical standing crop residue amounts for wind erosion control in the inland Pacific Northwest, USA

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ABSTRACT

Crop residue is an important factor influencing wind erosion of cultivated soils. Establishing soil surface protection afforded by standing crop residue is critical for land managers seeking to reduce or prevent soil loss by wind erosion and the impacts of blowing dust from agricultural lands. The objectives of this study were to evaluate the effect of standing residue on soil wind erosion in the inland Pacific Northwest (iPNW), USA, and test the performance of the plant factor algorithm of the Agricultural Policy/Environmental eXtender (APEX) and Revised Wind Erosion Equation (RWEQ) models in influencing soil loss. The effect of standing winter wheat (*Triticum aestivum* L.), spring canola (*Brassica napus* L.), and chickpea (*Cicer arietinum*) residue on wind erosion, remaining from major commodity crops in the region, was tested in a laboratory wind tunnel using four levels of residue density. The impact of standing residue in controlling wind erosion was compared and analyzed in terms of residue density and their respective frontal area index. Our results show that residue at a density characteristic of the production environment (110 standing residue elements m^{-1} for winter wheat, 20 standing elements m^{-1} for canola, and 16 standing elements m^{-1} for chickpea) provided significant protection to the soil surface from wind erosion. Soil loss at this level of residue density was reduced by 73.3, 53.4, and 60.9% for respectively winter wheat, spring canola, and chickpea (frontal area indexes are 0.172, 0.104, and 0.026 respectively) compared with a surface without residue. The soil surface was found to be at significant risk from wind erosion when residue densities of the three crop types were < 50% of the typical production amounts. Although not consistently significant, soil loss decreased as wind direction shifted from parallel to perpendicular with the standing residue row. The APEX model adequately simulated winter wheat and spring canola residue protection but had low accuracy in representing chickpea residue effects relative to the wind tunnel experiments. In contrast, the RWEQ model appeared inadequate in simulating soil loss for the winter wheat and canola treatments but adequately represented chickpea residue effects. Differences in model accuracy for different crop types must be considered by producers and managers to determine whether model information used to select practices to control wind erosion are likely to result in under- or over-protection of soil resources.

1. Introduction

Crop residue is the plant material left in an agricultural field after a crop has been harvested. Crop residues have environmental and economic value associated with input of nutrients and organic matter to the soil, and biofuel production (Karlen et al., 1994; Rasmussen and Collins, 1991; Figuerêdo et al., 2020). Crop residue also has important effects of reducing wind friction speeds at the soil surface and surface abrasion by saltating soil grains (Shao, 2008; USDA, 2016), in addition to influencing soil aggregation and soil water content (Unger and Vigil, 1998; Kumar et al., 2019). Establishing soil surface protection afforded by crop residue is therefore important for producers seeking to prevent or reduce soil loss by wind erosion and the impacts of blowing dust from agricultural lands (Marzen et al., 2019; Feizi et al., 2019).

Information on critical cover levels at which aeolian sediment transport occurs for prostrate and standing crop residues can be used by managers as a target for avoiding or reducing wind erosion and blowing dust from agricultural lands (Zobeck et al., 2013). Crop residue could

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reduces soil water erosion as a result of increasing infiltration (Scopel et al. 2004), aggregate stability and soil microbial biomass (Verhulst et al., 2011). Conservation tillage leads to greater crop residue, thus reduces soil loss (Alliaume et al., 2014). Knowledge of critical amounts of residue can also be used to develop benchmarks to guide wind erosion monitoring, and to set monitoring objectives in support of broader land management and air quality objectives at the farm scale and regionally (e.g., Leys et al., 2018; Webb et al., 2020). For example, a producer with a management objective of reducing soil degradation by wind erosion from a field may set a monitoring objective to determine that 85% of the field has > 50% prostrate residue cover for the duration of the windy season, where 50% prostrate residue cover is the benchmark value above which wind erosion is controlled. The residue amount can be selected at, or below, the threshold at which wind erosion occurs depending on the desired level of soil protection (Miri et al., 2019). Critical residue amounts for controlling wind erosion and blowing dust will depend on crop type and management practices as they affect the structure and cover of the residue (roughness), and physical and aerodynamic protection (sheltering) of the soil surface relative to the inherent erodibility of the underlying soil (Walter et al., 2017). This means that, to inform management across agricultural systems, research is needed to establish crop-specific thresholds for aeolian sediment transport and the response of aeolian transport rates to different prostrate and standing crop residue amounts (Webb et al., 2020).

A growing body of research has established how different crops and crop residues moderate wind erosion. Much of this work has used laboratory or field wind tunnel and field measurements to examine the use of residue cover for wind erosion control (e.g., Lyles and Allison, 1976; Bilbro and Fryrear, 1985, 1994; Fryrear, 1985; Leys, 1991; Michels et al., 1995; Sterk and Spaan, 1997; Bielders et al., 2000; Li et al., 2007; Breshears et al., 2009; Burri et al., 2013; Van Pelt et al., 2017; Walter et al., 2017; Miri et al., 2019; Pi et al., 2020; Jarrah et al., 2020). The importance of standing crop residue on wind momentum absorption and aerodynamic sheltering was recognized early and a number of wind tunnel experiments using live and artificial plants have sought to establish standing residue effects for different crop types (e.g., Lyles and Allison, 1976; Hagen, 1996; Aiken et al., 2003; Cong et al., 2016). This research is supported by the extensive literature on momentum partitioning over different roughness arrays (e.g., Raupach et al., 1993; Crawley and Nickling, 2003; Pierre et al., 2014; Webb et al., 2014). Recent studies have sought to establish more integrative effects of residue management on wind erosion for different crop production systems from field measurements and mechanistic models (e.g., Touré et al., 2011; Funk and Engel, 2015; Pierre et al., 2018; Rakkar et al., 2019). Results from these studies can inform wind erosion management and provide references to managers to identify critical crop residue amounts for controlling wind erosion (Rakkar et al., 2019). However, even controlling for reside spacing and orientation relative to erosive winds, the moderating effects of crop residue on wind erosion can vary significantly between crop types (Lyles and Allison, 1981; Abdourhamane Touré et al., 2019). To establish effective targets for controlling wind erosion, research is needed to identify critical residue amounts for different crops and local management systems.

Wind tunnel experiments, field measurements and mechanistic modeling can be used to identify critical residue amounts for managing wind erosion in agricultural fields (Funk and Engel, 2015). Wind tunnel experiments arguably provide the greatest accuracy and precision, enabling control of residue types, amounts, structures and geometric spacing that can be guided by typical management practices (Zobeck et al., 2013). However, conducting wind tunnel experiments to elucidate effects of the wide variety of crops grown in regions susceptible to wind erosion would be prohibitively expensive and is generally unavailable as an approach for land managers and soil conservationists (Marzen et al., 2019; Gholami et al. 2016, 2019). Process-based wind erosion models can also be used to evaluate critical residue amounts and identify targets and benchmarks for wind erosion monitoring and management for different crop types and management practices. The effectiveness of wind erosion models for identifying critical residue amounts must be evaluated against field and wind tunnel measurements as they are used by managers and agencies (e.g., United States Department of Agriculture's Natural Resources Conservation Service, NRCS) to identify practices for controlling wind erosion.

In the inland Pacific Northwest (iPNW) of the United States (US), wind erosion and blowing dust are persistent issues for soil nutrient loss from agricultural fields, regional air quality and highway safety (Sharratt et al., 2007). The region spans eastern and central Washington, north-central Oregon, and northern Idaho, including the highly erodible loess soils of the Columbia Plateau used for dryland cropping (Elsner et al., 2010). An estimated 5.5 Mg ha^{-1} soil is eroded each year from the cultivated lands in the region (USDA-NRCS, 2015). Feng and Sharratt (2007; 2009) measured wind erosion from agricultural fields associated with high winds in the iPNW during 2003 to 2006. They found that the mean daily soil loss is 0.4 Mg ha^{-1} during high wind events.

Many crops are grown in the iPNW where non-irrigated soils are susceptible to wind erosion. Winter wheat (*Triticum* L.) – summer fallow is by far the predominate crop rotation used on windblown soils (Schillinger et al., 2006). There has been recent interest in intensifying this rotation by growing canola (*Brassica rapa*) and chickpea (*Cicer arietinum* L.) in rotation with wheat (Schillinger and Paulitz, 2018; Esser et al., 2018). Winter wheat has been grown in the iPNW since 1878, especially in the low-precipitation zone where winter wheat-summer fallow is practiced on 90% of cropland (Schillinger and Papendick, 2008; Schillinger et al., 2006). As demand increased for food and biofuel feedstocks by the aviation industry, land planted to canola in the USA increased ten-fold from 1991 to 2015 (Long et al., 2016). Pulse crops are grown on 115,000 acres in state of Washington, of which 80% is chickpea. Chickpea are a popular commercial crop due to their ease of storage and health benefits (Brouwer et al., 2016). Soils are typically susceptible to erosion during the summer fallow phase of the rotation due to traditional tillage practices burying crop residue and degrading soil aggregates. Intensifying the wheat-fallow rotation would reduce wind erosion (Sharratt and Schillinger, 2014).

The objectives of this study were to: (1) identify critical standing reside amounts to control wind erosion in the iPNW for each crop type under typical management practices (row spacing and planting densities), as well as identify the change in wind erosion with progressive changes in residue density for modeling purposes; and (2) evaluate the performance of two wind erosion models for independently identifying critical residue amounts that could inform management. We use wind tunnel experiments to quantify effects of winter wheat, canola and chickpea standing residues on aeolian sediment transport rates. We then apply the mechanistic Revised Wind Erosion Equation (RWEQ) and the Wind Erosion Stochastic Simulator (WESS) implemented in the Agricultural Policy/Environmental eXtender (APEX) model to test their utility for reproducing the experimental results and informing management.

2. Methods and materials

Soil loss influenced by standing crop residue was assessed for three dominant crops commonly found across the iPNW.

2.1. Soil preparation

Samples of Warden soil series (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids) were collected from the upper 30 mm of the profile at a field site near Paterson, WA (46°01′N, 119°37′W) for use in the wind tunnel experiments. Warden soil series is a major soil type in the iPNW and the site is a recommended sampling location based on local USDA-Natural Resources Conservation Service office (Sharratt and

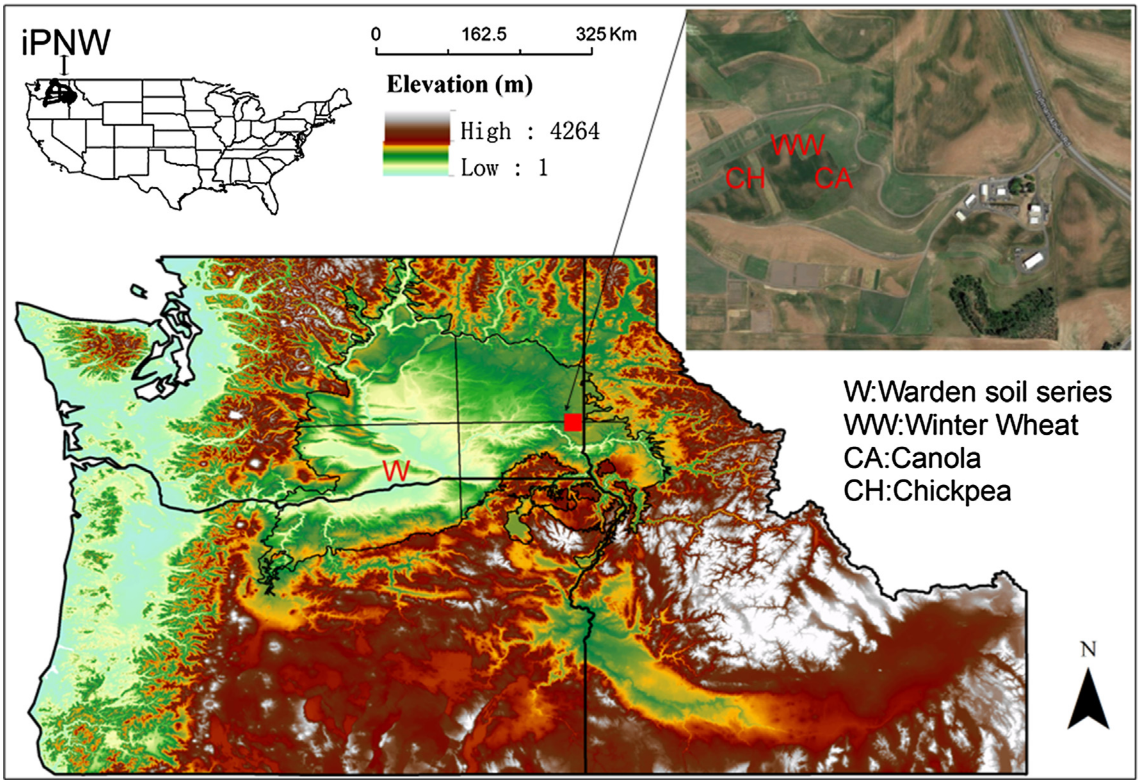

Fig. 1. Location of soil and crop sample sites across the inland Pacific Northwest, USA.

Vaddella, 2012). The soil series was previously used to assess wind erodibility characteristics in the region (Sharratt and Vaddella, 2014, Singh et al., 2012; Sharratt et al., 2013; Pi and Sharratt, 2019). The upper 30 mm of the soil was used to determine soil wind potential (Zobeck, 1991), because it is soil representative of near-surface conditions. This site is characterized by low precipitation (annual precipitation 200 mm) (Fig. 1) and has historically been in a winter wheat-summer fallow rotation (Sharratt and Schillinger, 2018). Warden soils are highly erodible due to their high sand content (67.2%) and low clay (9.6%) and organic matter (0.6%) content (Sharratt and Vaddella, 2012). Samples were collected from multiple sites within a 20 m radius of the field site. After collection, samples were stored a in plastic container for transportation to the laboratory where they were air-dried and hand-sieved through a 2 mm sieve to remove plant residue (Sharratt and Vaddella, 2012).

2.2. Standing crop residue preparation

Crop residue from winter wheat, spring canola, and chickpea were obtained after harvest. All crop types were grown at the Palouse Conservation Field Station (PCFS) near Pullman, WA which receives 530 mm of annual precipitation (Fig. 1). The PCFS has about 200 acres of rolling cropland. Residue height after harvest at the PCFS ranged from 10 to 30 cm for winter wheat, 8 to 15 cm for chickpea, and 10 to 30 cm for spring canola. Samples of residue stalks were harvested above ground from the field. Samples were then washed, air-dried, and cut to 10 cm lengths before wind-tunnel testing. In this study, we used a standardized standing residue height of 10 cm height for the three crop types. The average stalk diameter and biomass were determined for a minimum of 100 stalks in the field. The mean diameter was 3.44 mm for winter wheat, 6.70 mm for spring canola, and 2.87 mm for chickpea (Table 1).

Standing residue has been reported to significantly affect aeolian sediment mass flux (e.g., Lyles and Allison, 1980, 1976; Hagen, 1996). However, if not rooted, residue elements are susceptible to being blown offsite, especially under high winds. To avoid residue loss in the wind tunnel, we anchored the standing residue to soil trays using metal clamps. The clamps (8 mm tall) were used to secure and firmly hold the bottom-most (8 mm) portion of standing residue elements. The weight of the clamps allowed the standing residue elements to remain stable and in place under high wind regimes in the wind tunnel. We assumed the clamps played a similar role to roots in securing the residues.

We tested the effect of standing residue on wind erosion using standing residue configurations that result from typical management practices in the iPNW. Standing residue configurations were characterized by plant row spacing and in-row standing residue element population under in-situ field conditions. The configurations were determined at field sites near Paterson and Pullman, WA where winter wheat, spring canola, and chickpea were seeded in conventional rows having a plant-row spacing of respectively 17, 12.5, and 17 cm. The average in-row standing residue element population was 110 standing elements m^{-1} for winter wheat, 20 standing elements m^{-1} for canola, and 16 standing elements m^{-1} for chickpea. To test the effectiveness of standing residue on wind erosion, we varied the standing residue density of winter wheat, canola, and chickpea to 50, 100, and 200%. We kept the inter-row spacing consistent in all residue treatments. These treatments resulted in residue densities of respectively 55, 110, and 220 residue elements m^{-1} for winter wheat, 10, 20, and 40 residue elements m^{-1} for canola, and 8, 16, and 32 residue elements m^{-1} for chickpea. These configurations resulted in a surface standing residue frontal area index (λ) of respectively 0.086, 0.172, and 0.344 for winter wheat, 0.052, 0.104, and 0.208 for spring canola, and 0.013, 0.026, and 0.052 for chickpea (Table 2). The frontal area index (unitless) was determined as:

$$\lambda = nbh/s \tag{1}$$

where b is the diameter or breadth (m), h is height (m), n is the number of standing residue elements, and s is the ground surface area occupied by n standing residue elements. We measured the number of standing residue elements within each plant row. Frontal area index, also known

Table 1
Soil and residue parameters measured in the tray used to assess the influence of standing residue on wind erosion potential of three crops found across iPNW.

Parameters	Crop type	Frontal area index					
		Bare	1/2ST[1]	ST[1]	2ST	4ST	8ST
Water content (g g^{-1})	Winter wheat	0.58%	0.87%	0.61%	0.88%	–	–
	Spring canola	0.58%	0.60%	0.73%	0.59%	–	–
	Chickpea	0.58%	0.70%	0.48%	1.11%	0.68%	0.83%
Biomass, t ha^{-1}	Winter wheat	0.00	0.0767	0.153	0.307	–	–
	Spring canola	0.00	0.060	0.120	0.240	–	–
	Chickpea	0.00	0.023	0.046	0.092	0.185	0.370
Residue diameter, mm	Winter wheat	3.443	3.443	3.443	3.443	–	
	Spring canola	6.704	6.704	6.704	6.704	–	
	Chickpea	2.874	2.874	2.874	2.874	2.874	2.874
Soil wilting point water content (g g^{-1})	Winter wheat	6.64%	6.64%	6.64%	6.64%	6.64%	
	Spring canola	6.64%	6.64%	6.64%	6.64%	6.64%	
	Chickpea	6.64%	6.64%	6.64%	6.64%	6.64%	
GMD of aggregate size mm	Winter wheat	0.109	0.109	0.109	0.109	0.109	
	Spring canola	0.109	0.109	0.109	0.109	0.109	
	Chickpea	0.109	0.109	0.109	0.109	0.109	
Wind direction, degrees	All types	0, 45, 90	0, 45, 90	0, 45, 90	0, 45, 90	0, 45, 90	0, 45, 90

[1] ST is the standard level of residue density which is the measured residue density in the field.

Table 2
Soil loss of Winter wheat, Spring canola, and Chickpea at various levels of density measured inside a wind tunnel.

Crop type	Frontal area index					
	Soil loss (kg m^{-2})					
	Bare	1/2ST[1]	ST	2 ST	4 ST	8ST
Winter wheat	0	0.086	0.172	0.344	–	–
	3.22a[2]	1.65b	0.86c	0.61c	–	–
Spring canola	0	0.052	0.104	0.208	–	–
	3.22a	2.29b	1.50c	0.66d	–	–
Chickpea	0	0.013	0.026	0.052	0.104	0.207
	3.22a	2.03b	1.26c	1.18c	0.61d	0.43d

[1] ST is the standard level of residue density which is the measured residue density in the field.

[2] Soil loss means followed by the same letter for a given frontal area index are not significantly different at $P \leq 0.05$.

as lateral cover, has been used to parameterize drag partition schemes that represent momentum absorption and aerodynamic sheltering by roughness elements (e.g., Raupach et al., 1993). For the same planting density, the thicker stems of winter wheat and spring canola resulted in larger λ than for chickpea. Thus, we varied the residue density of chickpea to 400, and 800% to achieve λ of respectively 0.104 and 0.207 (Table 2). This allowed us to compare the three crop residue types in controlling wind erosion under a generally consistent range of λ. In all experiments, the same pattern of staggered rows was arranged to avoid any overlap (Fig. 2). We tested the effect of changing the geometric configuration of the crop residue relative to incident wind direction in the wind tunnel by altering the orientation of the plant rows from perpendicular with the wind tunnel working section. Three row orientations were tested at 0° (perpendicular to the wind tunnel working section), 45° and 90°.

After the standing crop residue was secured in aluminum trays (1 m long, 0.2 m wide, and 0.015 m deep), sieved Warden soil was placed in the trays until full. A metallic screed was used to level the soil surface so as to create a flat and uniform surface. Prior to preparing the experimental trays, soil and crop residue samples were placed in an oven at 105 °C for 24 h to dry. Soil water content was calculated by the reduction in weight of the sample by drying.

2.3. Wind tunnel assessment

The effect of standing winter wheat, spring canola, and chickpea residue on wind erosion was tested in a portable wind tunnel, which was powered by a 33 kW engine able to generate free-stream wind speeds of 2–20 m s^{-1} by a fan 1.4 m in diameter. The wind tunnel was 1.2 m tall, 7.3 m long with a working section 1.0 m wide, as described in detail by Pietersma et al. (1996). Total suspended particulate (TSP) concentration above the experimental trays during the wind tunnel tests was measured using E-samplers (Met One Instruments, Inc., Grants Pass, OR) which recorded TSP concentrations at 1 s frequency. The inlets (1 cm diameter) of the E-samplers were mounted at heights of 0.04, 0.06, 0.1, and 0.15, 0.2, and 0.3 m above the soil surface downwind of the soil tray. At the entrance of the working section of the tunnel, an E-sampler was installed to measure background TSP dust concentration. A Sensit (Model H11-LIN, Sensit Company, Portland, North Dakota) was used to measure saltation activity at a height of 5 cm on the downwind edge of the tray. Wind speed was measured using Pitot tubes which were attached to differential pressure transmitters. Differential pressures were measured at a 0.1 s frequency. Wind speed was measured at heights of 0.04, 0.06, 0.1, and 0.15, 0.2, and 0.3 m above the soil surface with data recorded every 1 s by a data logger. A relative humidity (RH) probe (Model CS500, Campbell Scientific Inc., Logan, Utah), atmospheric pressure and air temperature sensors (fine-wire thermocouples) were used to monitor the entrance of the wind tunnel. These parameters were measured 1.5 m above the floor, and were used to determine wind velocity and whether conditions were suitable for conducting the experiments. Days with air humidity greater than 50% were considered unsuitable to conduct the experiments because of humidity effects on the particle entrainment process (McKenna Neuman and Nickling, 1989).

Soil loss was determined by the weight difference of the experimental trays immediately before and after the wind tunnel runs. Freestream wind speed was systematically increased inside the tunnel from 2.0 to 7.5 m s^{-1} at a rate of 0.6 m s^{-1} every 15 s. Following this systematic increase in wind speed, the freestream wind speed was abruptly increased to 10 m s^{-1} and remained at that wind speed for 30 s to erode the soils. After each completed wind tunnel test, the E-samplers and pitot tubes were cleaned to eliminate the influence of residual dust on the next test. Systematically increasing wind speed also eliminated the disturbance of contaminants (e.g. external dust) entering the wind tunnel or perched particles emitted from the soil surface which

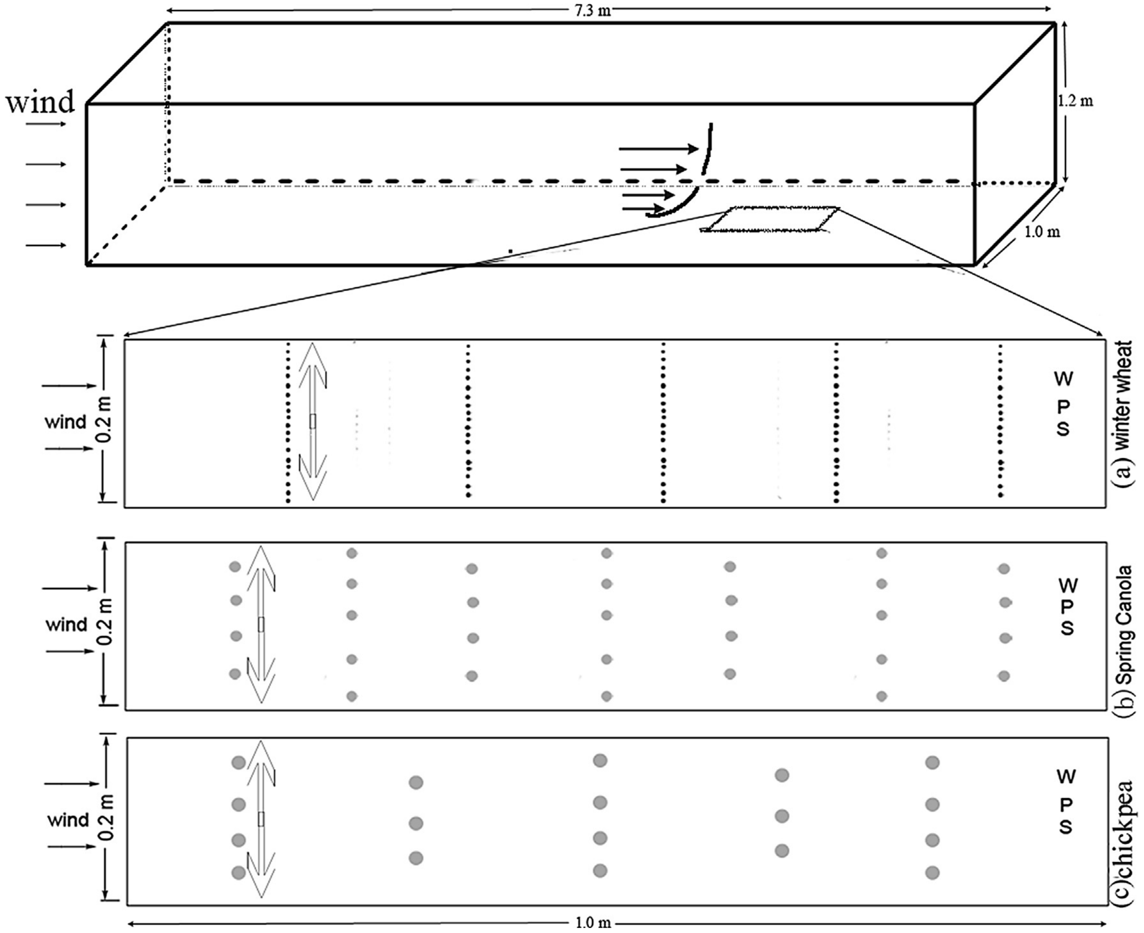

Fig. 2. Schematic of the wind tunnel test soil trays with standard level of residue density and configuration for winter wheat (a), canola (b) and chickpea (c). W = wind speed measurements, P = Total suspended particulate (TSP) concentration, S = Saltation activity measurements, hollow arrows = crop row orientation, which represents that crop row is perpendicular relative to wind direction.

may have produced instantaneous increases or spikes in saltation activity or TSP concentration.

We used the "soil loss ratio" (R_Q) to quantify erosion suppression by the standing crop residues (Sterk, 2000). The R_Q was calculated as:

$$R_Q = \frac{Q_R}{Q_S} \tag{2}$$

where Q_R is the soil loss in the presence of roughness elements, whereas Q_S is the soil loss with a bare surface. Soil loss ratios provide more information about crop treatment effects than actual soil loss (Bilbro and Fryrear, 1994).

2.4. Simulation of crop residue effects on wind erosion

We evaluated the performance of plant factor algorithms of two wind erosion models to independently identify critical residue amounts to control wind erosion. The models include the Wind Erosion Stochastic Simulator (WESS; Potter et al., 1998) implemented as a wind erosion submodel within the Agricultural Policy/Environmental eXtender (APEX) model, and the Revised Wind Erosion Equation (RWEQ; Fryrear et al., 1998). APEX is an integrated agricultural modelling system which has been used to evaluate various land management strategies for wind erosion management (e.g., Wang et al., 2012). APEX was developed from the Environmental Policy Integrated Climate (EPIC) model, a cropping systems model developed to estimate soil productivity as affected by erosion as part of the Soil and Water Resources Conservation Act analysis (Williams et al., 2012).

2.5. Model parameterization for crop residue types

The APEX wind erosion submodel was described in detail by Potter et al. (1998) and simulates soil loss following:

$$SL = SEF \cdot SRF \cdot VCF \cdot FFL \cdot Q_S \tag{3}$$

$$Q_S = \int_0^t \frac{ER}{WL} dt \tag{4}$$

where SL is simulated soil loss (kg m^{-2}); *SEF, SRF, VCF, FLF* are respectively the soil erodibility factor, surface roughness factor, vegetative cover factor, and field length factor, ER is the potential erosion rate (kg m^{-1} s^{-1}), WL is the unsheltered distance of wind across the field (m), and t is the duration (s) when the wind friction velocity (u_*) exceeds the threshold wind friction velocity (u_{*t}) of the surface. Q_S is the soil loss with a bare surface or the potential soil loss. A full description of the parameters used by APEX is given by Pi et al. (2017). In this study, *SEF, SRF, FFL, ER,* and *WL* were kept constant during all experimental runs. However, *VCF* was varied in analyzing the impact of crop residue on erosion. The *VCF* was calculated as:

$$VCF = 1 - \frac{X1}{[X1 + \exp(-0.331 - \alpha_{VCF} X1)]} \tag{5}$$

with

$$X_1 = (\omega 1SB + \omega 2SR + \omega 3FR) \tag{6}$$

where SB is the standing biomass (t ha^{-1}), SR is the standing crop residue (t ha^{-1}), FR is the flat crop residue (t ha^{-1}), and $\omega 1$, $\omega 2$, and $\omega 3$ are crop specific coefficients from the EPIC parameter database. In this

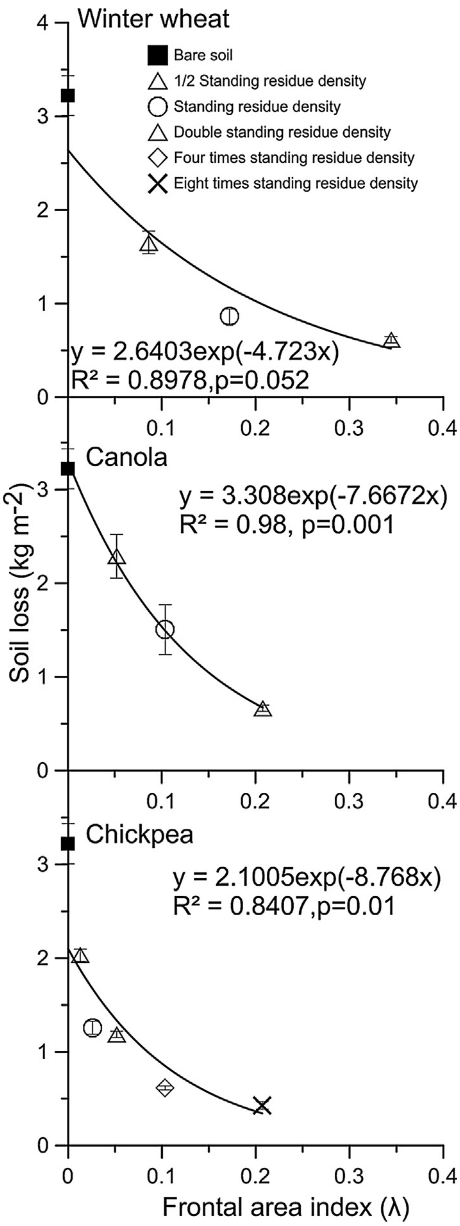

Fig. 3. Soil loss as a function of standing residue at 10 m s^{-1} freestream wind speed for three crop types found across inland Pacific Northwest.

study we used $\omega1$, $\omega2$, and $\omega3$ = 3.39, 3.39, and 1.61 for winter wheat, 1.266, 0.633, and 0.729 for spring canola, 1.266, 0.633, and 0.32 for chickpea residue respectively. The standing biomass for winter wheat, spring canola, and chickpea were on average 0.153, 0.515, and 0.388 g for each crop residue respectively.

Unlike APEX, which uses crop biomass to simulate the impact of residue on soil loss, the RWEQ uses the stem and leaf area index to simulate the influence of crop residues on soil loss. RWEQ estimates soil loss in the presence of a crop residue following:

$$Q_R = (e^{-0.0438(SC)} + e^{-0.0344(SA^{0.6413})} + e^{-5.614(CC^{0.7366})})Q_S \tag{7}$$

where SC is residue flat cover (%), SA is standing stem area index (cm^2 m^{-2}), and CC is fraction canopy cover (m^2 m^{-2}). Where Q_R is the soil loss in the presence of roughness elements, whereas Q_S is the soil loss for a bare surface. The standing stem area index for winter wheat, spring canola, and chickpea residues were 0.172, 0.104, and 0.026 respectively. A detailed description of RWEQ parameters can be found in Fryrear et al. (1998).

2.6. Model simulations and analysis

Verification of the AEPX and RWEQ models in simulating soil loss from surfaces with the three crop residues is needed to evaluate the utility of the models for informing crop residue management to control wind erosion. To verify the performance of the models, we compared measured soil losses from the wind tunnel experiments (Section 2.4) with soil losses simulated by APEX and RWEQ for the same ranges of crop residue densities (λ; described in Section 2.2) with input wind speeds of 10 m s^{-1} as used in the wind tunnel experiments. We used standard statistical tests to evaluate model performance, including calculation of the Nash Sutcliffe model efficiency (NSE), Willmott index of agreement (*d*), and coefficient of determination (R^2). The NSE (Nash and Sutcliffe, 1970) and *d* are described by:

$$NSE = 1.0 - \left[\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{\sum_{i=1}^{N}(Oi - \bar{O})^2}\right] \tag{8}$$

and

$$d = 1.0 - [\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{\sum_{i=1}^{N}(|Pi - \bar{O}| + |Oi - \bar{O}|)^2}] \tag{9}$$

where Pi, o_i and $\bar{O}$are respectively the predicted, measured, and average value and N is the number of comparisons. Values of *d* range from 0 to 1.0, with higher values indicating better agreement between measured and simulated values (Willmott, 1981).

2.7. Statistical analysis

Soil wind erosion from winter wheat, canola, and chickpea standing residue treatments was analyzed for differences using commercial software (SPSS Statistics 20.0; The SPSS Inc., Chicago, IL). One-way analysis of variance (ANOVA) was used to examine the effect of standing residue on soil loss. Normality tests were conducted prior to the ANOVA tests. Regression analysis was used to identify the relationship between soil loss and crop residue density and lateral cover and also between soil loss and row orientation with respect to wind direction. Values of $p < 0.1$ indicated that independent variables are statistically significant (10% level).

3. Results and discussion

The standard level of residue measured after crop harvest at the PCFS provided significant protection to the soil surface from wind erosion. Overall, we found that soil loss due to wind erosion was reduced by 73.3%, 53.4%, and 60.9% for winter wheat, spring canola, and chickpea compared with the surface in the absence of these residues (Table 2). These results suggest that the different crop residue types provided different levels of protection to the soil surface from wind erosion. Winter wheat was more effective in reducing soil loss than spring canola and chickpea.

3.1. Impact of standing crop residue amount on wind erosion

Soil loss was 32–74% smaller for winter wheat than spring canola and chickpea under standard residue density at 10 m s^{-1} wind speed (Fig. 3). In addition, TSP concentrations for winter wheat were lower than for spring canola and chickpea under standard residue densities (Fig. 4). This was expected because of the larger frontal area index (λ) for winter wheat than spring canola and chickpea under standard residue density (Fig. 3). The chickpea residue provided greater protection than the other two residue types at the same roughness density (Fig. 3). For example, soil wind erosion potential was 1.65, 1.54, and 0.87 kg m^{-2} for winter wheat, spring canola, and chickpea residue at λ = 0.1. This indicated a different pattern of protection for winter

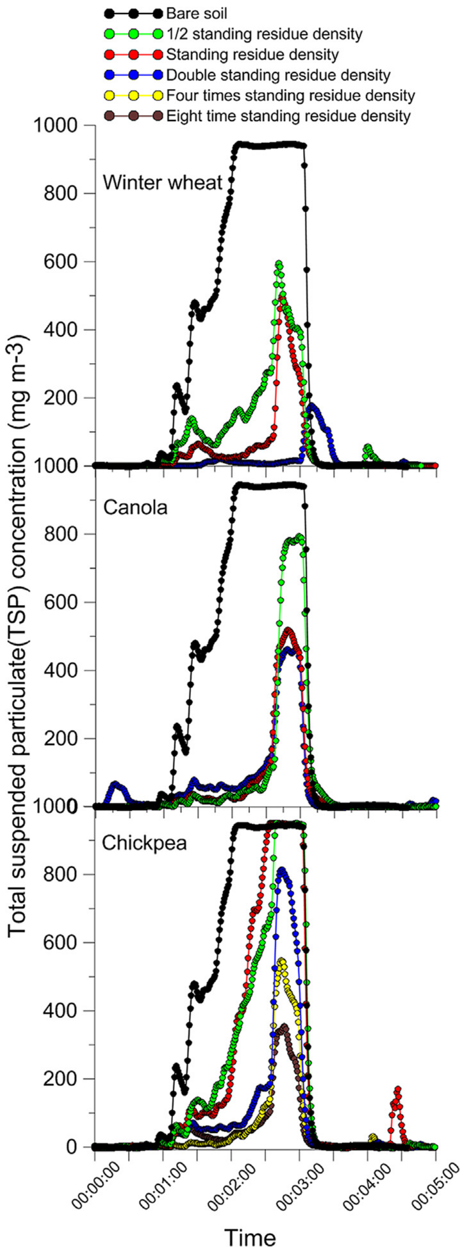

Fig. 4. Total suspended particulate (TSP) concentration above the soil surface of standing residue for three crop types as a function of time inside the wind tunnel.

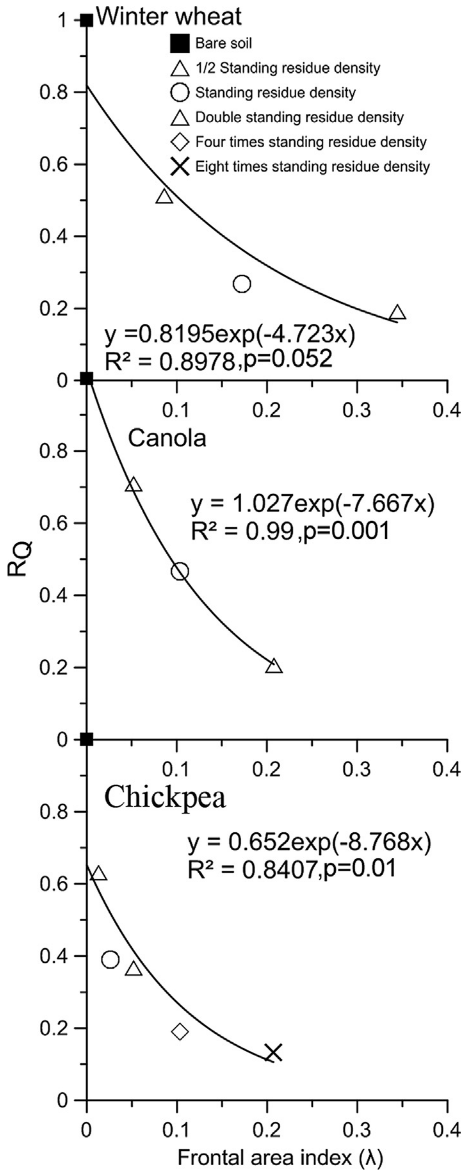

Fig. 5. Soil loss ratio as a function of standing residue at 10 m s^{-1} freestream wind speed for three crop types found across inland Pacific Northwest.

wheat, spring canola, and chickpea residues.

Differences in soil protection afforded by the three crop residues can be explained by the different morphological structures of the residues. The chickpea standing residue was characterized by irregular, curved and inflexible elements with multiple small branches while spring canola and winter wheat residues were characterized by straight and hollow elements without branching. The irregular chickpea residue (irregular, curved and multiple branches) may produce more mechanical turbulence around an element compared with spring canola and winter wheat with more streamlined shapes. These findings are consistent with those of Walter et al. (2012) and Funk and Engel (2015), who found that shear-stress partitioning and wind erosion may be different between plants with different morphological characteristics. In addition, differences in stem flexibility of the three crop stubble types may also be a reason for differences in soil loss because the flexibility of vegetation is a factor in determining effectiveness in reducing erosion (Udo and Takewaka, 2007). Winter wheat residue was hollow with a fragile epidermis. Although spring canola residue was not hollow, the stems were filled with tender parenchyma. Chickpea residue was characterized by a hard epidermis and stem, thus the stubble did not easily bend when subject to high wind speeds (i.e., 10 m s^{-1}).

The wind tunnel experiments revealed an exponential decrease in soil loss due to wind erosion with increasing frontal area index (λ) of the crop residues (Fig. 3). A similar relationship was found between frontal area index and R_Q (Fig. 5) for the three standing crop residues. This relationship was consistent with previous studies for a variety of crop types (e.g., Fryrear, 1985; Leys, 1991; Sterk and Spaan, 1997; Burri et al., 2011; Funk and Engel, 2015). Analysis of variance (ANOVA) revealed significant differences in soil loss among some of the standing residue treatments (Table 2). Significant differences in soil loss were found between standard and 50% residue treatments for three crop types and indicated that the soil surface may face significant risk from wind erosion for the three residue types when the standing residue density decreases to 50% of the standard in the field. No significant differences in soil loss were found between standard and 200% residue treatments for winter wheat and 400 and 800% residue treatments for chickpea. This indicated that the standing residue protected soil surface for two of the three crop residue types used in this study until the standing residue density exceeded certain value in which case the protective effect of standing residue may have reached a peak. We assume soil loss will not decrease to zero because crops sown in rows cannot establish an ideal standing residue protective layer without any gaps.

Overall, the standard residue amounts (110 standing residue elements m^{-1} or $\lambda = 0.172$ for winter wheat, 20 standing elements m^{-1} or $\lambda = 0.104$ for canola, and 16 standing elements m^{-1} or $\lambda = 0.026$ for chickpea) measured after crop harvest at the PCFS provided significant protection to the soil surface from wind erosion. Actually, half of these standard residue amounts appeared to have a significant effect in reducing wind erosion (Table 2). This suggested that at least maintaining standing residue (55 standing residue elements m^{-1} for winter wheat, 10 standing elements m^{-1} for canola, and 8 standing elements m^{-1} for chickpea) is critical for protecting the soil surface from wind erosion.

3.2. Impact of crop row orientation to wind direction on wind erosion

Crop row orientation relative to wind direction had a measurable effect on wind erosion rates. Soil loss decreased as winds shifted from parallel to perpendicular with the standing residue rows in this study (Fig. 6). This was not surprising because the "effective frontal area index" increased as the effective wind direction was changed from parallel to perpendicular with the standing residue rows. As the wind direction then shifted from perpendicular toward parallel with the row (from 90 to 180°), the "effective frontal area index" decreased and soil loss increased again. Fig. 6 shows how soil loss varied with wind direction over the range of 0–90° row orientation for the three crop residue types. The rate of change in wind erosion with a change in row orientation relative to wind direction was higher for canola than chickpea and winter wheat. Soil loss was reduced by 32.5%, 35.0%, and 25.9% for winter wheat, spring canola, and chickpea when winds changed from 0 to 90°. We assume that these rates of change in wind erosion were associated with the residue diameters, which were 3.44, 6.70, and 2.87 mm for winter wheat, spring canola, and chickpea. Regression analysis between the rate of change in soil loss and residue diameter ($Y = 35.28x-6.58$, $R^2 = 0.64$) suggested that the soil loss rate may varied with residue diameter when winds changed from 0 to 90° under a consistent λ, but $p > 0.1$ indicated that soil loss rate and residue diameter are not statistically significant (10% level). This is due to the "effective frontal area index". When winds changed from 90° to 0°, there was a continuous effective shelter area along the row downwind of a standing residue element when the residue density was sufficient. The effective shelter area only depended on the residue diameter such that larger diameter stem (spring canola) resulted in the greater rates of change in soil loss than for the smaller diameter stem (winter wheat and chickpea).

For all crop residues, rows oriented perpendicular to the wind resulted in most surface protection and smallest soil loss due to wind erosion. Sowing crops in rows perpendicular to the predominant erosive wind direction, or planting crops in circular rows (e.g. around a center pivot) would be most effective for reducing wind erosion. This finding is consistent with previous research and highlights the need for information about roughness orientation to interpret effects on wind erosion at a given λ (Fryrear, 1985; Leys, 1991; Sterk and Spaan, 1997; Burri et al., 2011; Funk and Engel, 2015).

3.3. Simulated soil losses and protection by standing crop residues

Soil losses simulated by APEX and RWEQ as a function of standing residue for three crop types are shown in Fig. 7. Both models indicated a similar influence of standing residue on erosion: simulated soil loss decreased with the increasing standing residue. Both models were sensitive to the standing residue. APEX simulated soil losses for winter wheat and spring canola were reduced by 56% and 20% relative to the surface in the absence of the residues. These effects were consistent with the wind tunnel measurements. However, APEX simulated soil loss for chickpea was only reduced by 8%, which was less than the wind tunnel measurements (60.9%). Measured and APEX simulated soil loss for all standing residue treatments are given in Fig. 8. The results showed acceptable agreement between the measured and simulated soil loss for all standing residue treatments with $d \geq 0.6$ and $R^2 \geq 0.5$ for winter wheat and canola. The results suggest that APEX could be used to assess the influence of winter wheat and spring canola standing residue on wind erosion but may be less useful for evaluating the effectiveness of chickpea residue for wind erosion control. The APEX plant factor algorithm was developed from laboratory wind tunnel studies by Lyles and Allison (1980, 1981), who determined the plant impact on erosion using seven crops: cotton, forage sorghum, canola, silage corn, soybeans, sunflowers, and winter wheat. Our interpretation is that the model inadequately simulated soil loss for chickpea due to the different morphological structures of the residue canopies as compared with the crops used in the APEX development.

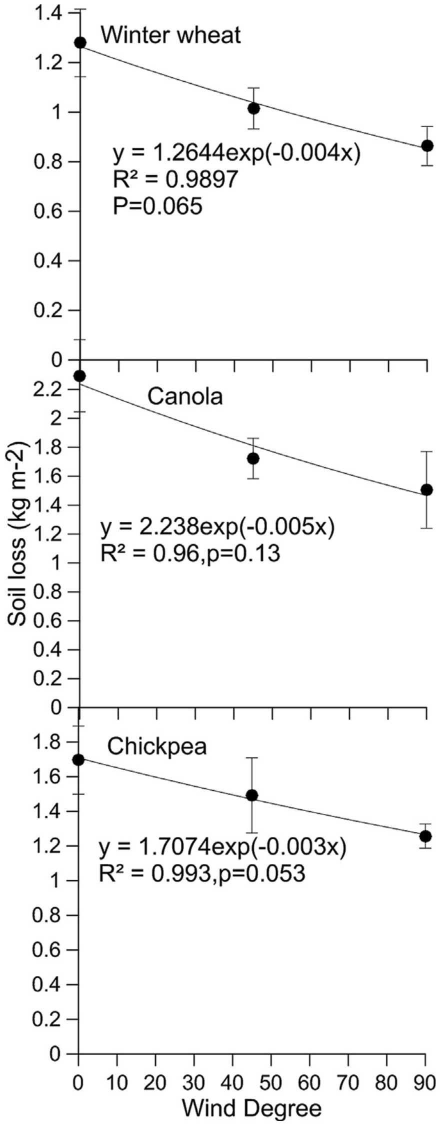

Fig. 6. Soil loss decreased with intersection angle between wind and standing residue row in the range 0° to 90°.

RWEQ overestimated the protection of standing residue for the three crop residue types. Simulated RWEQ soil losses for winter wheat,

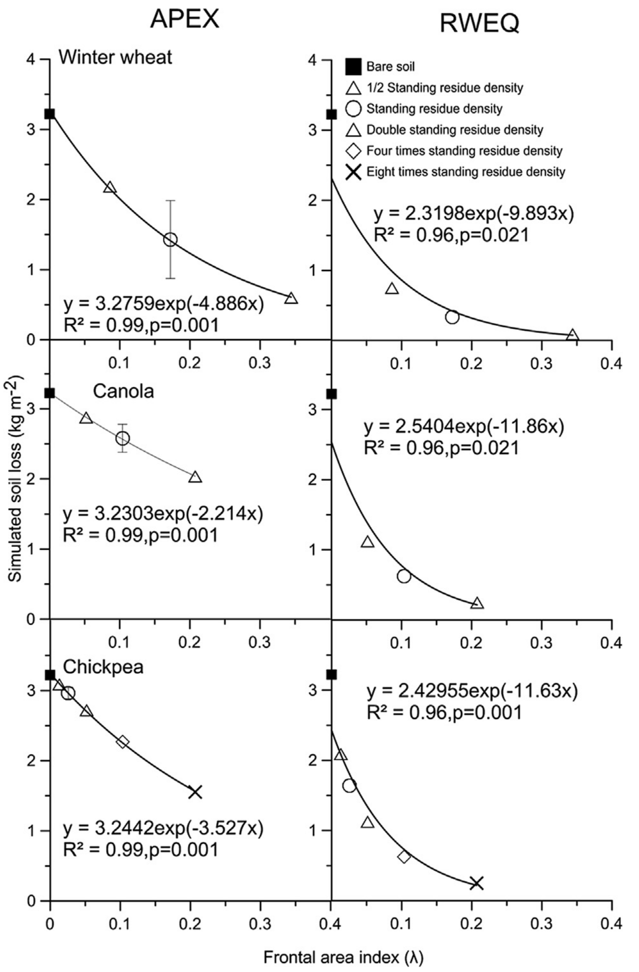

Fig. 7. Soil loss simulated by the APEX and RWEQ models as a function of standing residue at 10 m s^{-1} freestream wind speed for three crop types found across inland Pacific Northwest.

spring canola, and chickpea were reduced by 90%, 81%, and 49% relative to bare soil surfaces. These results amount to an overestimation of crop residue effectiveness in reducing wind erosion by a factor of two (Table 2). The RWEQ model appeared inadequate for simulating soil loss for the winter wheat and canola treatments as indicated by $d < 0.6$. In contrast, there was acceptable agreement between measured and simulated RWEQ soil loss for the chickpea treatment with $d > 0.6$ and $R^2 > 0.5$.

We interpret differences in model performance representing the effects of the crop residues on soil loss with respect to how the two models represent residue surface protection and aerodynamic sheltering. The RWEQ model uses λ to simulate the impact of standing residue on erosion while the APEX model uses crop biomass to simulate the impact of residue on erosion (Table 1). The standing residue distribution on the soil surface is shown in Fig. 2. The lee position of the stem can be described as an "effective shelter area" where there is reduced shear stress on the surface. The shear stress partition model developed by Raupach et al. (1993) envisions no shear stress at the surface downwind of a stem. Okin (2008) expanded their theory to describe how the lowest shear stress occurs immediately at the lee position of the stem and then increases until the shear stress approaches the shear stress for an equivalent non-vegetated surface. While plant or stem structure may affect the shear-stress distribution, the minimum shear-stress occurs downwind of the stem while the maximum shear-stress is detected at the front or lateral position. Bradley and Mulhearn (1983) indicated the distance for recovery of the shear stress ranged from 4.8 to 10 times the height of the roughness element. This is to say, the superimposed shelter areas would be reached at approximately 48 cm from the first upwind standing residue element. Thus, the revised "effective frontal area index" in RWEQ should be about 20% of the frontal area index shown in Fig. 2. Based on the "effective frontal area index", RWEQ showed acceptable agreement between measured and simulated soil losses for all standing residue treatments (Fig. 8). This suggested that the standing residue distribution significantly influenced shear stress in terms of determining the "effective frontal area index".

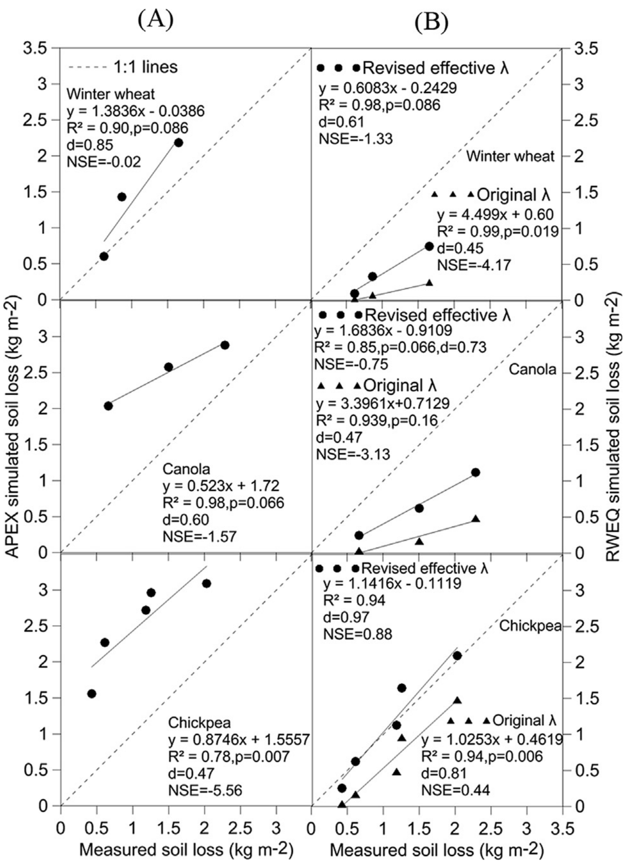

Fig. 8. Statistical comparisons of measured and simulated soil loss based upon original APEX (A) and RWEQ (B) simulations, *d* is the index of agreement. The RWEQ simulations were poor based on original λ (triangle) of standing residue, but improved based on revised effective λ (circle).

In all experiments, the same pattern of staggered rows was arranged to avoid any overlap (Fig. 2), thus "effective frontal area index ratio (effective frontal area index/ ideal frontal area index)" may be high for low density residues. This is a reason that RWEQ adequately simulated soil loss for chickpea, but inadequately simulated soil loss for winter wheat and canola; i.e., because the density was lower for chickpea than winter wheat and chickpea. Actually, there were relatively smaller differences (24–27%) between the measured and simulated soil loss by RWEQ under low density residue ($\lambda \le 0.026$ or density ≤ 16 stems m^{-1}), but larger differences (59–93%) between the measured and simulated soil loss under higher density residues ($\lambda > 0.026$, or density > 16 stems m^{-1}).

3.4. *Using wind tunnel measurements and models to inform crop reside management for wind erosion control*

In this study, we evaluated the effect of standing winter wheat, spring canola and chickpea residue on soil wind erosion. We found the standard residue amounts measured after crop harvest at the PCFS provided significant protection to the soil surface from wind erosion. The APEX and RWEQ wind erosion models revealed a similar influence of standing residue on erosion, with differences in the accuracy of the models relative to the wind tunnel experiments emerging as a function of how they represent standing residue effects on the erosion process. On the basis of our validation, APEX more accurately assessed the influence of winter wheat and spring canola standing residue on wind erosion, whereas RWEQ appears to provide a more accurate assessment of the influence of chickpea residue on erosion. For all crop residues, rows oriented perpendicular to the wind resulted in most surface protection and smallest soil losses due to wind erosion.

Land use types and agroecological classes have been expected to shift under future climate scenarios, for example, the dynamic grain fallow class will likely increase 63% in area of the iPNW (Kaur et al., 2017). Grain fallow is associate with lower crop residue, thus may result in the hazard of soil wind erosion (Sharratt et al., 2007). In addition, potential increases in land development associated with increasing food demands may increase the regional hazard of soil wind erosion in the future.

4. Conclusions

This study sought to identify critical winter wheat, canola and chickpea reside amounts to control wind erosion in the iPNW under typical management practices (row spacing and planting densities). Consistent with previous studies, we found soil loss decreased exponentially with increasing frontal area index of the winter wheat, canola and chickpea residues. The three crop residue types provided different levels of protection to the soil surface from wind erosion. Winter wheat residue was more effective in reducing soil loss than spring canola and chickpea residues. Residue amounts of 110 standing residue elements m^{-1} or $\lambda = 0.172$ for winter wheat, 20 standing elements m^{-1} or $\lambda = 0.104$ for canola, and 16 standing elements m^{-1} or $\lambda = 0.026$ for chickpea residue measured after crop harvest provided significant protection to the soil surface from wind erosion and even half of these residue amounts appeared to be effective in reducing wind erosion by 48.8, 28.9, and 37.0% for winter wheat, spring canola, and chickpea relative to an unprotected (bare) soil surface. Soil loss was exponentially related to wind direction, with winds perpendicular to residue rows being more effective in reducing soil loss than other row orientations relative to incident winds.

We found that the wind erosion models produced similar responses of decreasing erosion within increasing residue when applied to simulate the crop residue effects on wind erosion. However, we also found differences in model performance that indicate, following standard parameterization of the models for the different crop residues, APEX more accurately represented winter wheat and canola residue effects than chickpea while the RWEQ model more accurately represented chickpea residue effects on wind erosion. Differences in model fidelity and sensitivity to crop residues should be considered alongside model accuracy by managers using models to identify critical crop residue amounts for controlling wind erosion. Model accuracy for different crop types and management strategies must be clearly reported to producers and managers so that they can consider whether model information used to select practices to control wind erosion are likely to result in under- or over-protection of soil resources.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104742.

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