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Short Communication

Harvest index–yield relationship for estimating crop residue in cold continental climates

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ABSTRACT

Soil carbon (C) balance largely depends on the amount of crop residue inputs into soils and those inputs are affected by harvest index (HI), the ratio of harvested product to total shoot dry matter. The objective of this study was to establish the relationship between HI and yield for major crops to improve the estimation of aboveground crop residue inputs to agricultural soils in cold continental climates. We analyzed yield and HI data for 11 major crops from published field studies in a cold continental climate. Significant linear relationships between HI and crop yield were determined for wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), pea (*Pisum sativum* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* L.), soybean (*Glycine max* L.), canola (*Brassica napus* L.), and flax (*Linum usitatissimum* L.) (R^2 = 0.19–0.65, $P < 0.05$), while HI of potato (*Solanum tuberosum* L.) did not change with yield. The HI increased by 0.015 for wheat and maize to 0.110 for flax for each Mg ha^{-1} yield increase. Results for wheat, lentil, flax, and maize showed that crop HI was significantly influenced by grain yield ($P < 0.01$) but not significantly ($P > 0.05$) affected by cultivar when the grain yield effect was included. These results indicated that cultivar effect appears to be largely captured through crop yield, so it does not appear to be essential to know the cultivar to estimate the HI for an annual series of regional yields from different cultivars. The developed relationships between HI and crop yield allow improved estimation of residue inputs in cold continental climates.

1. Introduction

Soil carbon (C) sequestration in agroecosystems is one of the most promising greenhouse gas mitigation options (Lal, 2004). The soil organic C (SOC) content reflects a balance between C input and the loss through decomposition, erosion and leaching/runoff. SOC increases when C input to soil exceeds SOC decomposition. However, this increase will not continue indefinitely, and will reach equilibrium when C input balances SOC decomposition (Janzen et al., 1998). Despite the dynamic C balance of the soil, reports have shown that the equilibrium level of SOC within a cropping system can be related linearly to the amount of crop residue applied to the soil (Mandal et al., 2007; Fan et al., 2014). Therefore, accurate quantification of regional scale crop residue inputs is critical for designing effective policies and management practices that can contribute toward mitigating anthropogenic greenhouse gases emissions (Zhang et al., 2015).

Crop residue inputs to agricultural soils are mainly from shoot and root residues, and rhizodeposition (Chirinda et al., 2012). These residues not only play a pivotal role in replenishing SOC but also benefit nutrient pools and soil conditions such as reduced soil erosion, soil moisture retention (Zhao et al., 2015).

There is limited data on residue input of different crops (Kuzyakov and Domanski, 2000; Wiesmeier et al., 2014). Several approaches had been proposed to estimate the crop residue input to agricultural soils from widely available data on harvested yield (Johnson et al., 2006; Bolinder et al., 2007; West et al., 2010). These approaches use the HI, and root to shoot ratio to calculate crop residue inputs from harvested yield. However, HI data used in their estimation have relied on invariant fixed average HI value for individual crops based on literature. Globally, crop yield and HI have increased since the Green Revolution of the 1960s (Wiesmeier et al., 2014; Zeng et al., 2014) due to genetic improvement from crop breeding (Kumudini, 2002; Johnson et al., 2006). The increase of

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HI for different crops was significantly correlated with grain yield of wheat (Reynolds et al., 1999), barley (Bulman et al., 1993), soybean (Schapaugh and Wilcox, 1980), and canola (Ali et al., 2003). Recently, Wiesmeier et al. (2014) found a mean increase of cereal HI from 0.35 in 1951–1955 to 0.45 in 1995–2010 in southeast Germany by reviewing historic and recent data, which revealed increase of the aboveground residue input by 17–251% for cereals. The use of fixed HI values would introduce different errors along an annual time series if crop HI changed over time. Therefore, a more precise estimation of crop residue input is necessary to monitor the input of plant residue C into agricultural soils over time.

The objective of this study was to establish the relationship between HI and crop yield for major crops through a literature review to improve the estimation of crop aboveground residue inputs to agricultural soils in cold continental climates.

2. Materials and methods

2.1. The database

A dataset was compiled to estimate the relationship between harvest index (HI) and grain yield for major crops in cold continental climates by searching databases of Scopus and Google Scholar for literature in English. Only field studies reporting both crop yield and HI (or measurements from which HI could be calculated) were included in the analysis. Canadian literature was primarily used to provide a coherent dataset regarding management practices and locality to represent and compare the behavior of major crops for cold continental climates. However, oat data from Canadian literature was insufficient to establish a significant relationship between HI and grain yield, where dataset were expanded to the global area of cold continental climates. A total of 91 studies with 416 pairs of data were included in the dataset for the analysis. Some references included multiple sites, year, or crops per study. For each study, we also noted the location, latitude and longitude, experiment year, crop cultivar (Table S1). For reference with different treatments, the treatment with moderate fertilization level and/or without water and other stress was used. The data from references were separated into 11 crops: wheat, maize, oat, barley, pea, chickpea, lentil, soybean, canola, flax, and potato.

2.2. Analysis of relationship between harvest index and yield for major crops

Based on inspection of the data, we selected a linear equation to describe the relationship between HI and yield as follow:

$$HI_i = \alpha_i \times Y_i + \beta_i \quad (1)$$

where i denotes different crops. HI_i represents the harvest index; Y_i is the harvested yield (Mg DM ha^{-1}); α_i captures the change rate of HI_i with Y_i; β_i is the intercept of the relationship. Mean value and 95% confidence interval (CI) of the slope and intercept of Eq. (1) for each crop were generated by bootstrapping with 1999 iterations. For crop with no significant relationship between HI and yield, the averaged HI value and 95% CI were also generated by bootstrapping with 1999 iterations. Eq. (1) was also used to derive a relationship between HI and crop yield for crop groups of cereals (wheat, maize, oat, and barley), pulse crops (pea, chickpea, and lentil), oilseed crops (soybean, canola, flax) or grain crop (all crops in this study excluding potato).

The analysis of covariance (ANCOVA) is used to compare regression lines by testing the effect of categorical factor (crop type) on HI while controlling for the effect of yield (Rogosa, 1980).

2.3. Annual time series and cultivar evaluation

A long-term rotation experiment was used to establish the impact of cultivar on the relationship between HI and crop yield. The "Old Rotation" experiment (Campbell and Zentner, 1993) was initiated in 1966 at Swift Current Research and Development Centre, Agriculture and Agri-Food Canada in Swift Current, Saskatchewan (50°17′N, 107°48′W). It is a semiarid environment with 30-year mean annual temperature of 4 °C and precipitation of 351 mm. The soil is a silt-loam Orthic Brown Chernozem with about 2% organic carbon and 0.2% total N in the upper 15 cm depth and a pH of 6.5.

Our study considered three rotation treatments – fallow-wheat–wheat (F-W-W), lentil-wheat (L-W), and fallow-flax-wheat (F-Flx-W) – all with recommended N and P fertilizer rates. The F-W–W rotation used a series of Canada western hard red spring wheat varieties: Chinook in 1967–1974, Canuck in 1975–1982, Leader in 1983–1989, Lancer in 1990–1996, AC Barrie in 1997–1999, AC Eatonia in 2000–2005, and Lillian in 2006–2014. The L-W rotation likewise used a series of lentil varieties: Laird in 1979–2000, Sovereign in 2001–2008, and CDC Improve Clearfield Variety in 2009–2014. Varieties of flax in the F-Flx-W rotation were Dufferin in 1980–1992, Vimy in 1993–2011, and CDC Bethune in 2012–2014. Analysis of covariance (ANCOVA) was used to investigate the influence of yield and cultivar on crop HI of wheat, lentil, and flax within the annual time series, taking cultivar as a factor and remaining yield as covariate.

A similar ANCOVA was used to evaluate the effect of maize yield and cultivar (maize cultivars developed from crossing inbred lines are termed hybrids) on HI for a two-year experiment during 2008 and 2009 with 9 hybrid types at the Emile A. Lods Agronomy Research Centre of McGill University in Sainte-Anne-de-Bellevue, Quebec (45°24′N, 73°56′W), using data extracted from Yanni et al. (2011).

3. Results

3.1. Relationship between HI and crop yield

There was no obvious non-linear relationship between HI and crop yield (Fig. 1). Significant linear relationships were determined for wheat, maize, barley, pea, chick pea, lentil, soybean, canola, and flax (Table 1). The slope of the regression equations, reflecting the change of HI per unit (Mg ha^{-1}) of yield increase, ranged from 0.015 for wheat and maize to 0.110 for flax (Table 1). No significant relationship between HI and yield was found for oat using data from Canada only (data not shown). By expanding the search to other areas with cold continental climate (Table S1), we were able to establish that its relationship between HI and yield was similar to other cereals (Fig. 1 and Table 1). The established equations explained 19–65% of the variation for different crops. However, no significant relationship between HI and yield was found for potato, a tuber crop, where average HI was 0.795 ± 0.014 (mean ± 95% CI).

The pairwise comparisons of HI-yield relationships between all crops based on ANCOVA analyses revealed that there were only three crop pairs for which the regression equations (intercept and slope) were not significantly ($P > 0.05$) different: barley and oat, lentil and chickpea, and flax and soybean (analyses not shown). Three general relationships were established for crop groups of cereals, pulse crops, and oilseed crops (Table 1). The slope reflects the average rate of increase of HI relative to yield increase. Cereals showed significantly ($P < 0.01$) lower slope (0.015) than either pulse crops (0.046) or oilseed crops (0.078) (analyses not shown). The slope for pulse crops was significantly lower than oilseeds. In general the intercept was inversely related to slope with cereals