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SHORT COMMUNICATION

Dry matter partitioning and residue N content for 11 major field crops in Canada adjusted for rooting depth and yield

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Abstract: To improve the estimates of C and N inputs to soil, we developed new estimates of partitioning between the harvested portion, aboveground residue, and belowground residue for 11 major crops based on depth-adjusted root/shoot ratios and grain yield-adjusted harvest indices. We updated the mean N concentration of each partition.

Key words: root/shoot ratio, straw, shoot, carbon, nitrogen, crop residue, roots.

Résumé : Pour mieux estimer les apports de C et de N au sol, les auteurs ont procédé à une nouvelle estimation de leur répartition entre la partie récoltée, les résidus superficiels et les résidus souterrains de onze grandes cultures en fonction du rapport racines/pousse corrigé selon la profondeur et de l'indice messianique ajusté selon le rendement grainier. Ensuite, les chercheurs ont actualisé la concentration moyenne de N de chaque fraction. [Traduit par la Rédaction]

Mots-clés : rapport racines/pousse, paille, pousse, carbone, azote, résidus culturaux, racines.

Introduction

More than 3.7 Pg of crop residues are produced worldwide each year and are one of the major sources of C to sustain cropland soil organic carbon (SOC) stocks (Lal 2004). Residue C (*i*) contributes new decomposable organic C that provides the energy that driving biogeochemical cycles, (*ii*) represents extracted atmospheric CO_2, and (*iii*) ultimately dictates the overall health and productivity of soils (Wang et al. 2016). In addition, globally, almost 12 Tg of N is contributed to the soil through crop residues (Cassman et al. 2002). The N concentration strongly governs the rate of residue decomposition (Janzen and Kucey 1988). Together, the C and N from crop residues are essential inputs to the belowground food web (Johnen and Sauerbeck 1977; Malhi et al. 2012). Owing to these indispensable roles of C and N, a precise and accurate estimation of C and N inputs from crop residues is critical to agro-ecological models and studies assessing nutrient budgets, carbon pools, soil organic matter (SOM), and soil quality (Bolinder et al. 2007; Fan et al. 2016).

Crop residues add C and N through (*i*) aboveground residues (AGR) (including stems, leaves, seed-holding plant structures, and threshable seed hulls) and (*ii*) the belowground (BGR) root biomass. The AGR for grain crops is often estimated using the harvest index (HI), the ratio of seed mass to total shoot mass (i.e., seed + AGR). The BGR is frequently estimated from shoot mass based on the root/shoot ratios (RSR). The RSR is the ratio of belowground plant biomass to aboveground plant biomass measured at or near maturity. The belowground biomass is based on observable roots and does not include difficult-to-measure belowground biomass lost in sloughed roots and rhizodeposition. The C deposition and RSR values vary widely among species due to differing root growth patterns (Jackson et al. 1996). For

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example, grasslands and savannahs tend to have high soil C stocks (Scurlock and Hall 1998) because perennial grass and forage species exhibit higher RSRs than annual species (Fan et al. 2016). Literature values for BGR are based on measurements taken from varying depths, creating inconsistencies in reported RSR values.

Based on literature review, Janzen et al. (2003) provided values for partitioning crop dry matter (DM) between grain yield (*G*), AGR, and BGR for a wide range of crops grown in Canada, and also provided estimates of N concentration for these DM components. This reference is widely used, including estimation of N input to soil for Canada's National Inventory Report on Greenhouse Gas Emissions (Environment and Climate Change Canada 2017).

Recently, Fan et al. (2017) analyzed published data and showed that there is a linear relationship between HI and *G*:

$$\text{(1)} \qquad \text{HI} = I_c + S_c \times G$$

where I_c and S_c are the intercept and slope of the relationship between HI and *G* for crop *c*. This relationship captures much of the HI variability due to growing conditions and cultivars and so improves estimates of AGR from *G*. Fan et al. (2016) also developed a set of root distribution functions with depth for 11 major crops for Canada, so that the observed RSR values can be adjusted to a uniform depth.

Our first objective was to incorporate recent developments in describing the root mass distribution with depth and the HI-yield relationship into a new approach to estimate the DM partitioning between *G*, AGR and BGR for 11 important crops in Canada: 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.), flax (*Linum usitatissimum* L.), alfalfa (*Medicago sativa* L.) and for a conglomerate of other forages: bromegrass (*Bromus inermis* Leyss), crested wheat grass (*Agropyron* spp.), fescue (*Festuca arundinacea* Schreb), red clover (*Trifolium pratense* L.), ryegrass (*Lolium* sp.), Russian wild rye (*Psathyrostachys juncea* Fisch.), sweet clover (*Melilotus officinalis* L.), switchgrass (*Panicum virgatum* L.), and timothy (*Phleum pratense* L.). Our second objective was to improve the estimates of mean N concentration of *G*, AGR, and BGR by adding new values from the literature to those already used in Janzen et al. (2003)

Materials and Methods

We compiled a dataset to adjust RSR to uniform soil depth for major crops and forages in Canada by searching databases of Scopus and Google Scholar. We added data from 58 studies (refer to the Supplementary data[1]; crop-wise), each comprising of one or more experimental datasets. New data points for mean calculations varied by biomass fractions and by crops. For example, new *G* mean for wheat included 195 new data points, whereas chickpea had mere two values. The data were aggregated for 11 field crops, and for alfalfa and other forages (bromegrass, crested wheatgrass, fescue, red clover, ryegrass, Russian wild rye, sweet clover, switchgrass, and timothy). For studies when the plants were grown in lysimeters outdoors or in containers within a greenhouse or when authors stated that the roots grown in the field had been sampled to maximum rooting depth, we assumed the RSR was for the whole root profile. Otherwise, the observed root mass used to calculate the RSR was adjusted to selected depth up to maximum rooting depth, $d_{\max}$, for each crop according to the following equation:

$$\text{(2)} \qquad R_d = R_{d_{\text{obs}}} \times \frac{1 + \left(\frac{d}{d_a}\right)^c + \left[1 - \frac{1}{1+\left(\frac{d_{\max}}{d_a}\right)^c}\right] \times d}{1 + \left(\frac{d_{\text{obs}}}{d_a}\right)^c + \left[1 - \frac{1}{1+\left(\frac{d_{\max}}{d_a}\right)^c}\right] \times d_{\text{obs}}}$$

where R_d is the root mass for selected depth, *d*; $R_{d_{\text{obs}}}$ is the root mass for the observed depth, d_{obs}; and d_a, $d_{\max}$, and *c* are fitted equation parameters for each crop (Fan et al. 2016). For forage crops, the fitted parameters were those derived for fescue (Fan et al. 2016). Mean values and 95% confidence interval were generated by bootstrapping with 1999 iterations using the "boot" function in R (Canty and Ripley 2012).

Equations 3–5 describe the relationships between major DM partitions. Because *G* is the most widely available plant production data from experiments and national statistics, a formulation is provided to calculate each of the other dry mater partitions from *G*.

$$\text{(3)} \qquad \text{DM}_d = G + \text{AGR} + \text{BGR}_d = [1 + \text{RSR}_d] \times \frac{G}{[I_c + S_c \times G]}$$

$$\text{(4)} \qquad \text{BGR}_d = \text{RSR}_d \times \left[\frac{G}{(I_c + S_c \times G)}\right]$$

$$\text{(5)} \qquad \text{AGR} = G \times \left[\frac{1}{(I_c + S_c \times G)} - 1\right]$$

where DM_d is the whole plant DM to soil depth of *d*, AGR is aboveground residue, BGR_d is belowground residue to depth *d* (note DM_d, AGR, and BGR are in same units as *G*), I_c and S_c are the intercept and slope of the HI-yield relationship for crop *c*, and RSR_d is the root/shoot ratio to a selected soil depth, *d*. From eqs. 3 to 5, it is useful to express partitions as a ratio to DM since all are then comparable on a common basis:

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjss-2017-0144.

$$\text{(6)} \quad \frac{G}{\text{DM}_d} = \frac{[I_c + S_c \times G]}{[1 + \text{RSR}_d]}$$

$$\text{(7)} \quad \frac{\text{BGR}_d}{\text{DM}_d} = \frac{\text{RSR}_d}{[1 + \text{RSR}_d]}$$

$$\text{(8)} \quad \frac{\text{AGR}}{\text{DM}_d} = \frac{[1 - I_c + S_c \times G]}{[1 + \text{RSR}_d]}$$

The literature values of N concentration used by Janzen et al. (2003) were updated with more recent literature reporting N contents of grain, straw, and (or) roots of the selected crops for Canadian studies. In some cases, we found no new information on N content (e.g., roots in flax). The AGR consists of a range of components, such as stems and leaves, but it was often unclear what components were included in measurements of N concentration although several references described the measured portion as stems. The average N contents in grain, root, and shoots were calculated from observing the following criteria (*i*) each year, location, and cultivar were treated as a separate data point; for example, a study evaluating two cultivars in 2 yr yielded four values for N content that were then included in calculation of species average, and (*ii*) when studies included fertilization or related treatments, values were individually scrutinized for variability and extreme values were excluded when the N content had greater than >25% variation from the overall experiment mean.

Results and Discussion

Our depth-adjusted values for RSR (Table 1) will be consistent with the measured values from the literature when all values are referring to the same depth of root mass determination. However, our depth-adjusted root mass estimates used for RSR will produce more comparable and consistent RSR values for a single specified depth than that derived from measured root data from multiple studies in which the depth over which roots were measured varied widely. An important advantage of our new depth-adjusted values is the ability to estimate root material input for a specific depth. From eq. 7 with Table 1, the mean partitioning of DM for grain crops to roots to 20 cm is 13%, whereas it is 20% to full rooting depth. The values available from Janzen et al. (2003) or Bolinder et al. (2007) do not enable distinction in root partitioning for different rooting depths.

For lentil, soybean, and flax, we found no new Canadian observations for N concentration in BGR (Table 2). Overall, we increased the number of observations of N concentration by about 40% compared with earlier work of Janzen et al. (2003) (data not shown). Still, many values remain based on small sample sizes. For six crops (oat, pea, chickpea, soybean, potato, and alfalfa), the sample size was seven or less for residue (Table 2). We took advantage of the increased sample sizes to calculate a measure of variation (i.e., standard deviation) that was not done in the earlier study (Table 2). As expected, the N concentrations from simply increasing sample size generally did not change N concentrations fundamentally after considering their underlying variability (Table 2). We attribute apparent changes in N concentrations from those in Janzen et al. (2003) to assumed better representation of the population by our larger sample of values from the literature. To illustrate, our mean N concentration of oat *G* was 24.26 g N kg^{-1} and appears higher than the 18 g N kg^{-1} value in Janzen et al. (2003). The latter value was based on a sample of only four points to which we added five more points to the sample and, therefore, presumably, the difference reflects a better estimate of the population mean due to the larger sample size. Another example of change we attribute to the effect of increasing sample size is our higher N concentration of canola AGR for which we added 13 new points to produce a nearly doubled total sample size of 27. The updated pea BGR N concentration (21.99 g N kg^{-1}) was twice the previous value (10 g N kg^{-1}). We found no original rigorous value of pea BGR N concentration within the references in Janzen et al. (2003) so our higher value is derived entirely from three new data points we included.

Compared with Bolinder et al. (2007) values for cereal crops (wheat, oat, barley, and maize), our values for entire root partition are all higher, their values did not all represent the whole rooting depth; when calculated for our RSR to 20 cm, the two data sets were comparable (results not shown). Our values for AGR were within 5% units of those in Bolinder et al. (2007) except for oat, where our value was higher. Because our partitioning to *G* varies considerably with yield, it is difficult to compare with constant values in other studies. For comparable crops in Janzen et al. (2003) and Bolinder et al. (2007), their *G* partition values are within 5% units of our values calculated from eq. 6 for typical yields (Table 3). Compared with our yield-adjusted partition values, the constant *G* partition values from these references will overestimate AGR for high grain yields and underestimate it for low grain yields. This not only lowers accuracy of AGR estimates over a range of grain yields in 1 yr but also compromises the accuracy of a time series of estimates whenever there is a yield trend. Fan et al. (2017) showed that the aboveground partitioning value for maize from Bolinder et al. (2007) was reasonable for mean Canadian grain yields during 2004–2009. Because maize yields have generally increased over time, the yield-adjusted partition value shows that the constant partition value would cause mean Canadian maize AGR to be underestimated before 2004 and overestimated after 2009. Higher yielding cultivars typically also have higher partitioning to *G* so that the yield-adjusted values also removes much of the cultivar effect on partitioning (Fan et al. 2017).

To estimate C input from our partitions, it is necessary to multiply the DM by carbon concentration. Bolinder et al. (2007) estimated the C concentration of all crop

Table 1. Root/shoot ratios (RSR) for different soil depth (cm) for major field and forage crops in Canada.

	Whole profile		0–20 cm		0–30 cm		0–60 cm		0–100 cm		
Crop	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	*n*
Wheat	0.229	0.206–0.257	0.128	0.114–0.143	0.157	0.141–0.177	0.196	0.176–0.220	0.217	0.194–0.243	22
Maize	0.250	0.224–0.278	0.149	0.134–0.166	0.178	0.157–0.197	0.218	0.196–0.243	0.242	0.217–0.269	23
Oat	0.419	0.279–0.519	0.269	0.179–0.334	0.308	0.208–0.384	0.374	0.250–0.464	0.419	0.279–0.519	7
Barley	0.210	0.146–0.332	0.136	0.094–0.215	0.157	0.110–0.242	0.184	0.128–0.291	0.200	0.139–0.316	21
Cereals	0.248	0.220–0.248	0.150	0.132–0.150	0.178	0.157–0.206	0.217	0.192–0.217	0.239	0.212–0.239	73
Pea	0.215	0.162–0.270	0.115	0.086–0.144	0.146	0.108–0.184	0.188	0.142–0.236	0.211	0.159–0.264	6
Chickpea	0.219	0.188–0.252	0.118	0.101–0.136	0.143	0.123–0.166	0.187	0.160–0.215	0.218	0.187–0.252	4
Lentil	0.239	0.215–0.276	0.155	0.140–0.180	0.179	0.162–0.207	0.217	0.195–0.250	0.239	0.215–0.276	4
Pulse crops	0.223	0.195–0.223	0.127	0.110–0.127	0.155	0.134–0.174	0.196	0.171–0.196	0.221	0.193–0.221	14
Soybean	0.224	0.178–0.264	0.135	0.107–0.159	0.150	0.121–0.177	0.177	0.141–0.209	0.198	0.158–0.233	5
Canola	0.375	0.267–0.474	0.236	0.168–0.298	0.260	0.191–0.332	0.316	0.224–0.399	0.369	0.262–0.466	6
Flax	0.193	0.178–0.210	0.079	0.073–0.086	0.125	0.117–0.137	0.179	0.165–0.194	0.193	0.178–0.210	12
Oilseed crops	0.246	0.216–0.246	0.131	0.109–0.131	0.166	0.144–0.205	0.213	0.189–0.213	0.238	0.208–0.238	23
Grain crops	0.245	0.223–0.273	0.144	0.130–0.161	0.172	0.157–0.192	0.213	0.195–0.237	0.237	0.216–0.263	110
Potato	0.097	0.073–0.111	0.059	0.044–0.068	0.068	0.051–0.077	0.084	0.062–0.096	0.097	0.073–0.111	12
Alfalfa and mixture											
All years	0.988	0.838–1.169	0.497	0.421–0.588	0.605	0.513–0.715	0.775	0.657–0.916	0.881	0.747–1.042	32
Establishment year	0.834	0.674–1.013	0.419	0.339–0.510	0.510	0.412–0.620	0.654	0.528–0.794	0.743	0.600–0.903	18
Production year	1.185	0.903–1.456	0.596	0.454–0.732	0.725	0.553–0.891	0.929	0.708–1.142	1.056	0.805–1.298	14
Other forages											
All years	0.868	0.723–1.028	0.538	0.448–0.638	0.626	0.521–0.741	0.766	0.638–0.908	0.868	0.723–1.028	61
Establishment year	0.618	0.524–0.738	0.384	0.325–0.458	0.446	0.378–0.532	0.546	0.463–0.652	0.618	0.524–0.738	36
Production year	1.213	0.970–1.513	0.753	0.602–0.939	0.875	0.700–1.091	1.072	0.857–1.336	1.213	0.970–1.513	25

Table 2. N concentrations of grain (*G*), aboveground residues (AGR), and belowground residues (BGR) of the major crops in Canada from Janzen et al. (2003) and from this study.

	N concentration (g N kg^{-1}; dry matter basis)								
	G			AGR			BGR		
Crop	Janzen et al. (2003)	This study[a]	*n*	Janzen et al. (2003)	This study[a]	*n*	Janzen et al. (2003)	This study[a]	*n*
Wheat	26	25.56 ± 4.11	448	6	6.64 ± 3.15	230	10	10.51 ± 1.49	21
Maize	15	12.72 ± 2.85	80	5	9.37 ± 2.59	54	7	7.55 ± 4.11	21
Oat	18	24.26 ± 9.38	9	6	6.83 ± 1.24	7	10	13.83 ± 3.32	3
Barley	19	20.79 ± 2.50	39	7	8.81 ± 3.84	21	10	12.39 ± 0.77	5
Dry pea	37	37.36 ± 11.6	13	18	21.02 ± 6.95	5	10	21.99 ± 3.49	3
Chickpea	ND	47.16 ± 20.0	2	ND	23.67	1	ND	14.98	1
Lentil	44	38.90 ± 3.51	18	10	11.72 ± 5.12	17	10	NU	NA
Soybean	67	62.51 ± 2.86	24	6	6.60 ± 1.92	7	10	NU	NA
Canola	35	38.15 ± 6.09	45	8	12.53 ± 5.76	27	10	8.83 ± 1.71	5
Flax	35	39.94 ± 5.10	20	7	12.20 ± 8.03	27	10	NU	NA
Potato	15	12.35 ± 3.22	29	10	13.02 ± 0.56	7	25	28.56 ± 20.9	5
Alfalfa	26	24.60 ± 4.31	17	15	13.80 ± 2.8	3	15	18.17 ± 4.46	6

Note: ND, not determined in Janzen et al. (2003) study; NU, not updated in this study since no new specific Canadian references found; NA, not applicable since no updates were performed; *n*, number of observations for this study.
[a]Mean values are followed by the standard deviations.

Table 3. Calculated plant partitioning of total plant dry matter (DM) into belowground residue (BGR) for entire crop rooting depth, into grain (*G*), and into aboveground residue (AGR), for dry-matter grain yields of 2, 4, and 8 t ha^{-1}.

				$G = 2$ t ha^{-1}		$G = 4$ t ha^{-1}		$G = 8$ t ha^{-1}	
Crop	I_c[a]	S_c[a]	BGR (% of DM)	*G* (% of DM)	AGR (% of DM)	*G* (% of DM)	AGR (% of DM)	*G* (% of DM)	AGR (% of DM)
Wheat	0.344	0.015	19	31	51	33	49	38	44
Maize	0.369	0.015	20	ND	ND	35	46	39	41
Oat	0.357	0.029	30	29	41	33	37	ND	ND
Barley	0.373	0.028	17	36	48	40	43	ND	ND
Pea	0.163	0.071	18	25	57	37	46	ND	ND
Chickpea	0.301	0.063	18	35	47	45	37	ND	ND
Lentil	0.305	0.059	19	34	47	ND	ND	ND	ND
Soybean	0.200	0.099	18	33	50	50	34	ND	ND
Canola	0.180	0.046	27	20	53	27	46	ND	ND
Flax	0.171	0.110	16	33	51	ND	ND	ND	ND
Potato[b]	0.795	0.000	9	ND	ND	72	19	72	19

Note: ND, not determined as the *G* values outside of range for which harvest indices were derived.
[a]I_c is the slope and S_c is the intercept of the harvest index-yield relationship for crop *c* (Fan et al. 2017).
[b]*G* for potato is harvested tubers.

partitions is 0.45 g g^{-1}. Additional belowground C input to soil would come from root exudates and sloughing. Bolinder et al. (2007) estimated that this additional C input for all crops is approximately 65% of the BGR based on measured roots.

Conclusion

In summary, we incorporated recent developments in describing the root mass distribution with depth and the HI-yield relationship into a new approach to estimate the DM partitioning between *G*, AGR, and BGR for 11 major field crops in Canada. This general approach is unique because it adjusts the belowground DM partitioning for a specified soil depth and adjusts the aboveground DM partitioning for harvested yield. We also updated the Janzen et al. (2003) estimates for N content in above- and belowground crop partitions based on literature survey. These developments will improve the estimates of C and N partitioning in the crops and, particularly, for estimates of C and N input from crop residues to the soil.

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