Net primary productivity and below-ground crop residue inputs for root crops: Potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.)

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Bolinder, M. A., Kätterer, T., Poeplau, C., Börjesson, G. and Parent, L. E. 2015. **Net primary productivity and below-ground crop residue inputs for root crops: Potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.)**. Can. J. Soil Sci. **95**: 87–93. Root crops are significant in agro-ecosystems of temperate climates. However, the amounts of crop residues for these crop types are not well documented and they need to be accounted for in the modeling of soil organic carbon dynamics. Our objective was to review field measurements of root biomass left in the soil as crop residues at harvest for potato and sugar beet. We considered estimates for crop residue inputs as root biomass presented in the literature and some unpublished results. Our analysis showed that compared to, for example, cereals, the contribution of below-ground net primary productivity (NPP) to crop residues is at least two to three times lower for root crops. Indeed, the field measurements indicated that root biomass for topsoils only represents on average 25 to 30 g dry matter (DM) m^{-2} yr^{-1}. Other estimates, albeit variable and region-specific, tended to be higher. We suggest relative plant DM allocation coefficients for agronomic yield (R_P), above-ground biomass (R_S) and root biomass (R_R) components, expressed as a proportion of total NPP. These coefficients, representative for temperate climates (0.739:0.236:0.025 for potato and 0.626:0.357:0.017 for sugar beet), should be useful in the modeling of agro-ecosystems that include root crops.

Key words: Roots, soil organic carbon, crop residues, agro-ecosystems, root crops

Bolinder, M. A., Kätterer, T., Poeplau, C., Börjesson, G. et Parent, L. E. 2015. **Productivité primaire nette et apport souterrain de résidus agricoles des légumes-racines : pomme de terre (*Solanum tuberosum* L.) et betterave sucrière (*Beta vulgaris* L.)**. Can. J. Soil Sci. **95**: 87–93. Les légumes-racines forment d'importants écosystèmes agricoles dans les régions à climat tempéré. Toutefois, on ne possède pas beaucoup d'informations sur la quantité de résidus agricoles que laissent ces cultures, alors qu'il faut en tenir compte lorsqu'on veut modéliser la dynamique du carbone organique du sol. L'objectif consistait à passer en revue les relevés pris sur le terrain de la biomasse racinaire demeurée dans le sol qui constitue des résidus de culture, à la récolte de la pomme et de la betterave sucrière. Les auteurs ont tenu compte de la quantité de résidus agricoles correspondant à la masse racinaire estimée dans la littérature et de quelques résultats non publiés. Leur analyse indique qu'à l'inverse des céréales, par exemple, la productivité primaire nette souterraine des légumes racines contribue deux à trois fois moins aux résidus agricoles. À dire vrai, selon les mesures prises sur le terrain, la biomasse racinaire dans l'horizon superficiel ne représente annuellement en moyenne que 25 à 30 g de matière sèche par m^2. D'autres estimations, quoique variables et spécifiques à une région, ont tendance à être plus élevées. Les auteurs proposent qu'on attribue un coefficient de répartition relatif de la matière sèche au rendement agronomique (R_P), à la biomasse aérienne (R_S) et à la biomasse racinaire (R_R). Ces coefficients sont exprimés comme une proportion de la productivité primaire nette. De tels coefficients, en étant représentatifs des régions à climat tempéré (0,739:0,236:0,025 pour la pomme de terre et 0,626:0,357:0,017 pour la betterave sucrière) devraient faciliter la modélisation des écosystèmes agricoles incluant des légumes-racines.

Mots clés: Racines, carbone organique du sol, résidus agricoles, écosystèmes agricoles, légumes-racines

Potato and sugar beet are important components of crop rotations in agro-ecosystems. Potato remains the fourth food crop (after corn, rice and wheat) for human consumption (FAOSTAT, faostat.fao.org) and sugar beet (after sugarcane) is responsible for about 20% of the world's sugar production (Anonymous 2009). The net exchange of CO_2 with the atmosphere depends on the balance between the amount of net primary productivity (NPP) and its proportion returned to the soil as annual C inputs that remains as soil organic carbon (SOC), and the release of CO_2 from the decomposition of native SOC through soil biological activity (Andrén et al. 1989; Paustian et al. 1997).

Abbreviations: **AG**, above-ground; **DM**, dry matter; **NPP**, net primary productivity; **SOC**, soil organic carbon

The potential for sequestration and long-term storage of atmospheric CO_2-C as SOC for different agro-ecosystems is usually examined with models. The main driving variable in these models is the annual C inputs to soil from organic amendments and above- and below-ground crop residues (Bolinder et al. 2006). The below-ground residue input (i.e., roots) is typically estimated from components of NPP (i.e., agronomic yields or above-ground biomass) based on root biomass measurements made in the field at the approximate time of peak above-ground biomass (i.e., close to harvest). Assumptions can also be made to account for rhizodeposition, i.e., extra-root material including root exudates and other material derived from root-turnover (Bolinder et al. 2007). Compared with the above-ground crop residue inputs, below-ground residue inputs are of particular interest because they are known to contribute more to stable SOC pools than above-ground residues (Kätterer et al. 2011).

For Canadian agro-ecosystems, Bolinder et al. (2007) reviewed literature data for common agricultural crops (cereals, soybeans and forages) and suggested an approach to estimate NPP and annual crop residue inputs to soil using relative plant allocation coefficients. Similarly, Gan et al. (2009) also derived Canadian-specific plant allocation coefficients for oilseed (canola, mustard and flax) and pulse (lentil, chick- and field-pea) crops. However, the above-mentioned as well as many other studies (e.g., Prince et al. 2001; Lokupitiya et al. 2010) on NPP and annual crop residue inputs to soil does not include any consideration for root crops such as potato and sugar beet.

Thus, there is a need to have accurate estimates of annual crop residue inputs to soil for root crops. This is important not only when predicting SOC trends over several decades, but also when these crops are present in long-term field experiments on which the SOC models are calibrated. For example, in some long-term field trials ($>$ 65 yr) root crops can represent up to 25% of the crop types present in the rotations (e.g., Carlgren and Mattsson 2001). Earlier (1950s) measurements from Germany, Russia and the Czech Republic summarized by Klimanek [1987; cited by Ludwig et al. (2007)] indicated that the average total amount of crop residues (i.e., above- plus below-ground) for potato and sugar beet represent about 200 and 100 g DM m^{-2} yr^{-1}, respectively. At present, with the exception of data obtained with crop growth models or inverse modelling approaches (e.g., Li et al. 1997; Meersmans et al. 2013), only a few general estimates for below-ground crop residue inputs to soil from root crops are available and they are not well documented. To our knowledge, no publication has addressed this issue in detail.

Our objective was to summarize the information available regarding annual crop residue inputs for root crops based on field measurements including some unpublished studies. We emphasize the contribution of the root system and suggest relative NPP allocation coefficients.

RESULTS AND DISCUSSION

Below-ground Crop Residue Inputs

We reviewed the available literature on root (excluding the tubers and beets) biomass measurements for potato and sugar beet that were made at or close to maturity from field studies at various locations and for different soil depths. Thereafter, these data are discussed with respect to other estimates used in the literature.

Root Biomass in Field Studies

Most of the studies we reviewed in Table 1 estimated the root biomass with conventional sampling techniques using soil cores, and only the study by Steen and Andrén (1990) measured the root biomass with ingrowth cores. For sugar beet, the two studies only measured fine roots. However, the coarse lateral roots that are attached to the beet are normally removed with the beets at harvest (Steen and Lindén 1987). The root biomass reported by Van Noordwijk et al. (1994) was also confirmed with measurements of fine root residue at harvest using minirhizotron techniques. The data from Bolinder and Parent (unpublished) were derived from a study conducted at seven on-farm sites from 2004 to 2006, under rain-fed conditions in eastern Canada (Québec). Briefly, three potato cultivars were grown on replicated large-plots on light-textured ($>$ 50% sand) soils. At each site, the experiments were conducted in large blocks; one cultivar was grown in each block with two to three replicates. Entire plants were sampled to determine both the above-ground (leaves and stems) and below-ground plant fractions (tubers and roots), which were expressed on a dry matter (DM) basis. Only the large roots that remained with the stems after pulling the plants were sampled. Bélanger et al. (2001) also sampled entire plants and only measured large roots. That study investigated the proportion of roots to total net primary productivity (shoots + tubers + large roots) for two cultivars, irrigated and non-irrigated that were subject to different N rates at two different sites over a 3-yr period.

The field measurements of total root biomass ranged from 13 to 96 and 28 to 40 g dry matter (DM) m^{-2} for potato and sugar beet, respectively (Table 1). However, on average, the total root biomass for potato and sugar beet were similar with about 35 g DM m^{-2}. Considering only roots in the topsoil layer (Table 1), the values were lower for sugar beet (i.e., 24 vs. 31 g DM m^{-2}). Potato is known as a shallow-rooted crop with most of its root biomass concentrated in the upper 20 to 30 cm soil layer (Joyce et al. 1979; Parker et al. 1989). Indeed, in the studies we found, only Mattsson (1991) sampled in deeper soil layers, the root biomass present below 25 cm represented about 20% of the total root biomass down to a 90-cm depth. Lescynski and Tanner (1976) sampled according to rooting depth. The proportion of roots below 25 to 30 cm for sugar beet represented up to about 35% of the total root biomass measured to a

Table 1. Root biomass (g dry matter m^{-2}) measured at or close to maturity in field studies for potato and sugar beet at various locations and for different soil depths (cm)

Study/location	Treatment/experiment	Total (and topsoil) sampling depth	Root biomass	
			Total	Topsoil
Potato				
Lescynski and Tanner (1976);	Conventional	40 to 70	68	–
US	Irrigated		46	46
Steen and Andrén (1990);	High C content soil	25 to 30 (25 to 30)	13	13
Sweden	Low C content soil		48	48
Mattsson (1991); Sweden	No N fertilization	90 (25)	96	76
Opena and Porter (1999); US	Irrigated + fertilized	30 (30)	16	16
Bélanger et al. (2001);	Non irrigated	30 (30)	16	16
eastern Canada[z]	Irrigated		19	19
Bolinder and Parent	cv. Goldrush	25 (25)	37	37
(unpublished); eastern Canada[y]	cv. Chieftain		26	26
	cv. Eramosa		14	14
Mean ± standard deviation			36 ± 26	31 ± 21
Sugar beet				
Steen and Lindén (1987);	No N fertilization	60 (25)	28	20
Sweden	N fertilization		31	20
Van Noordwijk et al. (1994);	Conventional system	100 (30)	36	23
Netherlands	Integrated system		40	31
Mean ± standard deviation			34 ± 5	24 ± 5

[z]Root biomass was calculated from the proportion of large roots to total net primary productivity and is presented for the irrigated and non-irrigated treatments averaged across N rates (not significant) and two cultivars ($N = 12$ observations for the study). The above-ground biomass was calculated from the harvest index of the same study (Bélanger et al. 2000).
[y]Each cultivar was subject to different N (130 to 250 kg N ha^{-1}) fertilization rates (N = a total of 16 observations for the study).

depth of 60 and 100 cm in the studies by Steen and Lindén (1987) and Van Noordwijk et al. (1994), respectively.

In the study by Bolinder and Parent (unpublished) the effects of N rates on root biomass (and marketable yields) were negligible (data not shown). However, there was a trend for a specific cultivar to have a different amount of root biomass (Table 1). The proportion of root biomass also tended to be greater for one of the cultivars in the study conducted by Bélanger et al. (2001) but their amount in terms of root biomass was similar. In that study, the response to irrigation was similar for both cultivars.

Approaches to Estimate Root Biomass from Agronomic Yields

There are some relationships that have been suggested in the literature for estimating the root biomass in the topsoil (down to 20 or 30 cm depth) layer as a function of the agronomic yield (i.e., tubers and beets) for potato and sugar beet (Table 2). Boiffin et al. (1986) mostly referred to values derived from the French literature. The Intergovernmental Panel on Climate Change (IPCC 2006) equations for root crops are based on general relationships between shoots and roots for other crops (according with the Tier 1 approach). The equations presented by Koga et al. (2011) are based on field measurements made in Japanese field experiments. For potato, Boiffin et al. (1986) suggest a fixed estimate.

The average yields from the Bolinder and Parent (unpublished) and the Bélanger et al. (2001) study on potato was approximately 6.5 Mg DM ha^{-1} (data not shown). Assuming a DM content of 20% (only wet weight yields were reported) the average yield was also about 6.5 Mg DM ha^{-1} in the Lescynski and Tanner (1976) study, but slightly higher (between 8 and 9 Mg DM ha^{-1}) in the Opena and Porter (1999), Mattsson (1991) and Steen and Andrén (1990) studies. Sugar beet yield was around 10 Mg DM ha^{-1} in the Steen and Lindén (1987) study. Based on the above-mentioned relations to agronomic yields, we estimated the crop residue inputs from root biomass of potato and sugar beet (Fig. 1). In these calculations we used a medium-yield value of 7.0 Mg DM ha^{-1} for potato and 10.0 Mg DM ha^{-1} for sugar beet so that they would reflect the average yields of these experiments.

Table 2. Relationships used to estimate dry matter (g m^{-2}) root biomass (RB) from the agronomic yield (AY) for potato and sugar beet

Reference	Potato	Sugar beet
Boiffin et al. (1996)[z]	$RB = 50$	$RB = 0.06 \times AY/0.94$
IPCC (2006)[y]	$RB = 0.02 \times AY + 21.2$	$RB = 0.02 \times AY + 21.2$
Koga et al. (2011)	$RB = 0.0827 \times AY$	$RB = 0.0146 \times AY$

[z]A fixed estimate is suggested for potato.
[y]Intergovernmental Panel on Climate Change. According to the Tier 1 approach.

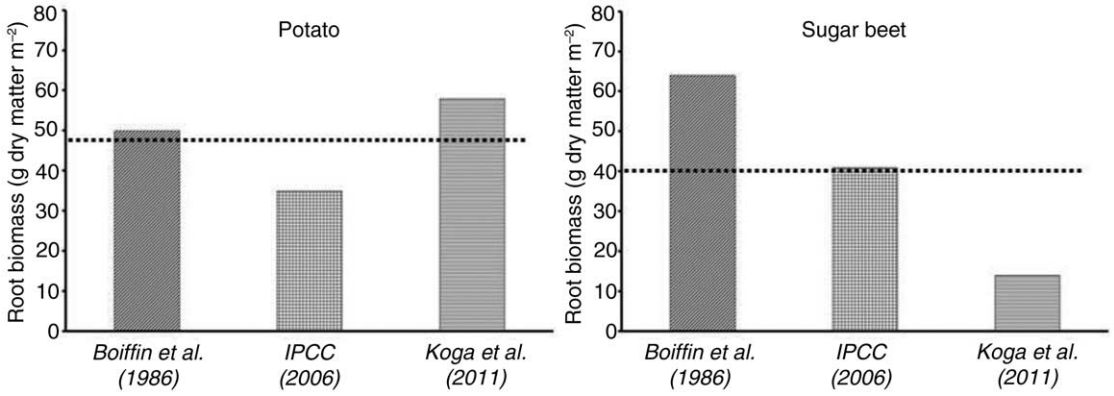

Fig. 1. Literature based values of crop residue inputs to soil as root biomass for potato and sugar beet considering estimates for an average yield of 7.0 and 10.0 Mg dry matter (DM) ha^{-1}, respectively. Dotted line = mean estimate (see the text for details).

The estimates of roots for potato ranged from 35 to 58 g DM m^{-2} and those of sugar beet from 14 to 64 g DM m^{-2} (Fig. 1). On average, the estimate for a potato crop was 48 g DM m^{-2} and that for sugar beet 40g DM m^{-2}. Compared with the field measurements for topsoil roots left in the field at harvest (Table 1) those estimates are 55 and 67% higher for potato and sugar beet, respectively. In particular, the root biomass for sugar beet would be over-estimated with the IPCC (2006) and Boiffin et al. (1986) equations, and under-estimated with that of Koga et al. (2011). However, it should be noted that the IPCC (2006) equation was not specific for sugar beet (it was modelled after potato). Another reference suggesting estimates of the annual crop residue inputs to soil from root biomass for potato and sugar beet is that of Soltner (2000). It is mainly an ''expert-opinion'' based assessment, suggesting a fixed value of 80 g DM m^{-2} for an average-yielding root crop, a value that seems too high according to our analysis (Table 1 and Fig. 1).

The IPCC (2006) gave the estimates that were closest to the average values from the field measurements for potato. However, application of the IPCC (2006) formula to calculate root biomass for potato, compared with the two data sets from eastern Canada with the most detailed information available from the Bolinder and Parent (unpublished) and Bélanger et al. (2001) studies resulted in an over-estimate of about 25 and 150% for these two data-sets, respectively (data not shown). Similarly, the Koga et al. (2011) equation resulted in an over-estimate of approximately 100 and 200%, respectively (data not shown). The IPCC (2006) equation also under-estimated a few data for the Bolinder and Parent (unpulished) study.

We used the two eastern Canadian data sets, which made similar measurements of root biomass for potato (with a mean root biomass of 22 ± 9 g DM m^{-2}; $N = 28$) to derive a specific equation to estimate root biomass from the agronomic yield (Fig. 2.). The Bélanger et al. (2001) root biomass data were slightly better correlated with the agronomic yields ($R^2 = 0.35$) than the Bolinder and Parent (unpublished) data ($R^2 = 0.27$). The combined relationship ($R^2 = 0.26$) was $RB = 0.0339 \times AY$. Compared with the same type of equation presented by Koga et al. (2011) it can be noted (Table 2) that this combined relationship yields a root biomass that is approximately two times lower. Our correlation for the combined relationship between final tuber yields and root biomass measured close to maturity was of the same magnitude (i.e., $R^2 = 0.31$) as that found by Opena and Porter (1999) in the United States. A calculation with measurements (to a depth of 25 cm) made in another study by Tran and Giroux (1991) from a ^{15}N fertilizer (applied in selected micro-positions within the main plots) trial in eastern Canada also corroborates our relationship. The equation derived with those data was $RB = 0.0328 \times AY$ ($R^2 = 0.61$ with $N = 10$, data not shown); the mean root biomass was the same as for the Bélanger et al. (2001) and Bolinder and Parent (unpublished) studies.

In the case when no regional-specific relationships are available, the average value of 31 g DM m^{-2} we calculated from the measurements of root biomass in topsoil for all studies on potato (Table 1) would constitute a reasonably good fixed approximation, recognizing the fairly high variability associated with root biomass estimates. The general IPCC (2006) equation for root crops would also be an alternative.

For other annual crops such as, for example, a medium-yield small-grain cereal (4 Mg DM ha^{-1}) and grain-corn (8 Mg DM ha^{-1}), annual crop residue inputs to soil from roots range from 130 to >250 g DM m^{-2}, respectively (Bolinder et al. 2007). For a potato crop, however, assuming that there are also approximately 5% of the tubers that are not harvested because they are too small or simply lost during the harvest operations (the IPCC (2006) default value for such a consideration is 8% of the marketable yield) this would increase the below-ground crop residue inputs for a medium-yield potato crop by 35 g DM m^{-2} (i.e., 0.05×7.0 Mg DM ha^{-1}). For most crop types, it is also common to

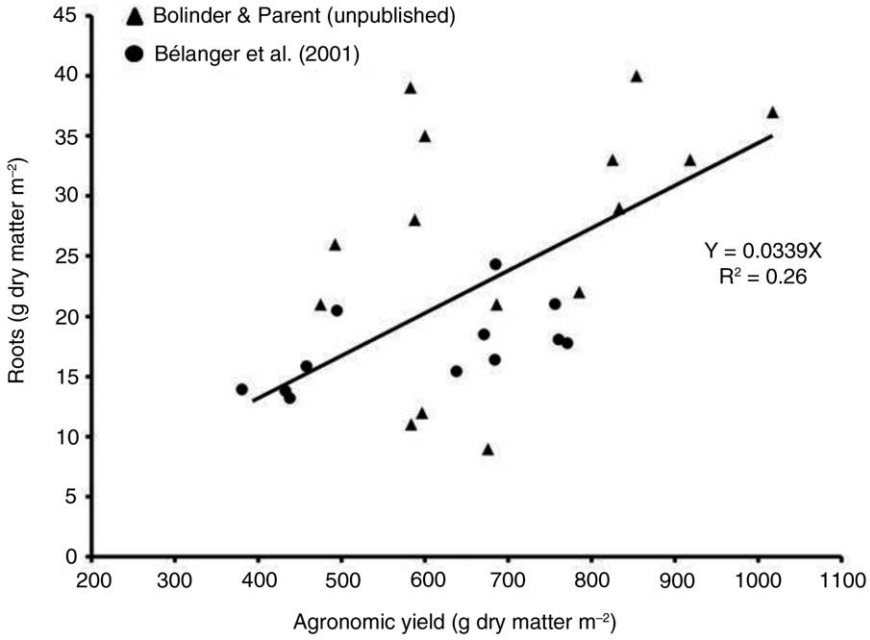

Fig. 2. Relationshsip between the agronomic yield (marketable tubers) and the measured root biomass for potato with the data from Bolinder and Parent (unpublished) and Bélanger et al. (2001).

include a coefficient to account for extra-root components, i.e., carbon from dying and decomposing roots as well as cell sloughing of epidermal root tissues during the growing season, including soluble compounds released from the roots by exudation (Kätterer et al. 2011). For example, Bolinder et al. (2007) and Gan et al. (2009) used a coefficient of 0.65 (i.e., extra-root components $= 0.65 \times RB$) for cereals, soybeans, forages, oilseed and pulse crops. The contribution of extra-root components to the below-ground crop residue inputs has mostly been assessed for small-grain cereals, forages and natural grasslands (e.g., Kuzyakov and Domanski 2000; Gill et al. 2002). There is also a contribution from extra-root that occurs for root crops (e.g., root turnover during the growing season), but there are to our knowledge no studies available that have quantified this contribution as a whole (i.e., taking into account all parts of the extra-root components). Nevertheless, compared with other annual crops, crop residue inputs from root biomass for a potato and sugar beet crop remain much lower.

Above-ground Crop Residue Inputs

The estimation of above-ground (AG) crop residues (i.e., potato vines) returned to the soil for potato as a function of the marketable yields are somewhat complicated by the fact that there is typically a vine killing (chemical) that takes place a few weeks prior to harvest. During maturation the tubers also accumulate additional dry weight, while the dry matter in tops decreases because there is carbon translocation to the tubers (Westermann 1993). Therefore, for a potato crop it is difficult to have simultaneous measurements for AG biomass and agronomic yields (as tubers) at harvest. Boiffin et al. (1986) considered AG crop residue from potato as negligible, and Soltner (2000) suggested no value. The AG crop residues were also measured in the root studies by Bolinder and Parent (unpublished) and by Bélanger et al. (2001). According to these data we used the average relationship $AG\ crop\ residue = 0.32 \times AY$, where the proportions of crop residues in the two studies represented 0.26 ± 0.11 and 0.37 ± 0.19, respectively. For an average yield of 7.0 Mg DM ha^{-1} this amounts to AG crop residues in the range of about 180 to 260 g DM m^{-2}. The proportions used in IPCC (2006) are 0.27 ± 0.04.

Contrary to potato, the above-ground biomass for sugar beet is more important but can often also be exported from the field and used, e.g., for animal feed. The studies on root biomass for sugar beet (Table 1) did not make a detailed discussion on measurements for the proportions of AG crop residues as a function of the agronomic yields, only the Steen and Lindén (1987) study indicated that it was about 40%. However, to have a robust estimate we examined this relationship from a Swedish database for long-term (initiated in 1957) field experiments where this relationship is periodically being assessed. Averaged across six of these soil fertility experiments located in southern Sweden for the period 1964–1972 [calculated from data in Jansson (1975)] indicated that it was $AG\ crop\ residues = 0.46 \times AY$ for normal to high PK and N fertilization rates (140 to 210 kg N ha^{-1}). The variability between sites [calculated from data in Agerberg (1961)] was fairly low (coefficient

of variation ≈10%). The relationships are continuously revised in this database and the average relationship (unpublished data) of $AG\ crop\ residues = 0.57 \times AY$ is used since the mid-1990s (for the same N application rates mentioned above). This is similar to the equation (i.e., $AG\ crop\ residues = 0.6 \times AY$) suggested by Boiffin et al. (1986). Therefore, if AG crop residues are left in the field, according to the latest relationship used in the Swedish database, they would represent about 570 g DM m^{-2} for an average-yielding (10.0 Mg DM ha^{-1}) sugar beet crop, a value that is twice as high as that for a potato crop. A fixed value of 400 g DM m^{-2} was suggested by Soltner (2000).

Relative Net Primary Productivity Allocation Coefficients

We calculated allocation coefficients relative to NPP. This was done following the approach described in detail by Bolinder et al. (2007), but excluding the extra-root component. Briefly, the NPP is partitioned into three coefficients (relative to total NPP) as follows: $R_P = C_P/NPP$, $R_S = C_S/NPP$ and $R_R = C_R/NPP$. Where C_P = the agronomic yield (tubers), C_S = above-ground biomass and C_R = root biomass. By definition $R_P + R_S + R_R = 1$. These coefficients are then used to calculate the corresponding value of each NPP constituent, usually as a function of C_P, e.g., $C_S = (R_S/R_P) \times C_P$.

When using the relationship determined with the most detailed data available, for the two data sets for eastern Canada (Fig. 2), and the average proportion as above-ground biomass from these two studies, the coefficients for potato are as follows: 0.739: 0.236: 0.025. For sugar beet, calculating the NPP allocation coefficients using the average data of field measurements available for roots in the topsoil (Table 1) and the latest relationship for above-ground biomass in the Swedish database, the coefficients for sugar beet are: 0.626: 0.357: 0.017.

The uncertainty in these coefficients is related to the variability in the yield data and in the above- and below-ground biomass measurements. For the two potato datasets, the coefficient of variation (CV,%) was 25% for the marketable yield and 46% for the above-ground biomass, representing fairly typical variations in field experiments. For the root biomass measurements it was 40%. With respect to root biomass, the variations in measurements are generally high. For example, the CV associated with the measurements reviewed for small-grain cereals and forages in Bolinder et al. (2007) was 80 and 70%, respectively, similar to that reported for other reviews (Amos and Walters 2006; Bolinder et al. 2012). However, these relative allocation coefficients can be refined, and the uncertainty reduced when new measurements for root crops emerge. Our knowledge on below-ground allocation remains limited and more field measurements are needed.

CONCLUSIONS

The review of field measurements and other available generic relationships in this study indicates that the annual root-derived crop residue inputs to topsoil for average-yielding potato and sugar beet crops are in the range of about 30 to 50 and 25 to 40 g DM m^{-2}, respectively. This contribution of below-ground NPP to annual crop residue inputs to soil for root crops are much lower compared with those for other annual crops, regardless of whether extra-root components and un-harvested tubers are also accounted for. The eastern Canadian-specific relative NPP allocation coefficients proposed for potato are complementary to those previously suggested for other commonly grown crops in Canada. These results should contribute to a better modeling of SOC dynamics for agro-ecosystems that include root crops.

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