

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/216804836>

An approach for estimating net primary productivity and annual carbon input to soil for common agricultural crops in Canada

Article in *Agriculture Ecosystems & Environment* · January 2007

Impact Factor: 3.4 · DOI: 10.1016/j.agee.2006.05.013

CITATIONS

180

READS

64

5 authors, including:



Ma Bolinder

Swedish University of Agricultural Sciences

31 PUBLICATIONS 1,515 CITATIONS

SEE PROFILE



H. H. Janzen

Agriculture and Agri-Food Canada

211 PUBLICATIONS 9,614 CITATIONS

SEE PROFILE



E. G. Gregorich

Agriculture and Agri-Food Canada

166 PUBLICATIONS 8,328 CITATIONS

SEE PROFILE



Bert Vandenbygaart

Agriculture and Agri-Food Canada

49 PUBLICATIONS 1,813 CITATIONS

SEE PROFILE



Review

An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada

M.A. Bolinder^{a,*}, H.H. Janzen^b, E.G. Gregorich^c, D.A. Angers^a, A.J. VandenBygaart^c

^a *Soils and Crops Research and Development Centre, Agriculture and Agri-Food Canada,
2560 Hochelaga Blvd, Sainte-Foy, Que., Canada G1V 2J3*

^b *Lethbridge Research Centre, Agriculture and Agri-Food Canada, 5403 1st Avenue South, Lethbridge, Alta., Canada T1J 4B1*

^c *Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada,
KW Neatby Building, 960 Carling Avenue, Ottawa, Ont., Canada K1A 0C6*

Received 22 November 2005; received in revised form 20 April 2006; accepted 3 May 2006

Available online 23 June 2006

Abstract

The current interest in characterizing, predicting and managing soil C dynamics has focused attention on making estimates of C inputs to soil more accurate and precise. Net primary productivity (NPP) provides the inputs of carbon (C) in ecosystems and determines the amount of photosynthetically fixed C that can potentially be sequestered in soil organic matter. We present a method for estimating NPP and annual C inputs to soil for some common Canadian agroecosystems, using a series of plant C allocation coefficients for each crop type across the country. The root-derived C in these coefficients was estimated by reviewing studies reporting information on plant shoot-to-root (S:R) ratios ($n = 168$). Mean S:R ratios for annual crops were highest for small-grain cereals (7.4), followed by corn (5.6) and soybeans (5.2), and lowest for forages (1.6). The review also showed considerable uncertainty (coefficient of variation for S:R ratios of $\sim 50\%$ for annual crops and $\sim 75\%$ for perennial forages) in estimating below-ground NPP (BNPP) in agroecosystems; uncertainty was similar to that for Canadian boreal forests. The BNPP (including extra-root C) was lower for annual crops ($\sim 20\%$ of NPP) than for perennial forages ($\sim 50\%$). The latter was similar to estimates for relative below-ground C allocation in other Canadian natural ecosystems such as mixed grasslands and forests. The proposed method is easy to use, specific for particular crops, management practices, and driven by agronomic yields. It can be readily up-dated with new experimental results and measurements of parameters used to quantify the accumulation and distribution of photosynthetically fixed C in different types of crops.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Roots; C inputs; C allocation; Uncertainty; Agroecosystems; Natural ecosystems

Contents

1. Introduction	30
2. Estimates of root biomass in Canadian agroecosystems	30
2.1. Description of experiments	30
2.2. Sampling procedures and methods for root separation	32
2.3. Shoot-to-root ratios and sampling depth	34
3. Proposed method for estimating total annual NPP, C allocation, and C input to soil	35
3.1. NPP and C allocation	35
3.2. Annual C inputs to soil	36
3.3. Assumptions used in calculations	36

* Corresponding author. Tel.: +1 418 657 7985x271; fax: +1 418 648 2402.

E-mail address: martinbolinder@yahoo.ca (M.A. Bolinder).

3.3.1.	Harvest index	36
3.3.2.	Shoot:root ratios	36
3.3.3.	Extra-root C	37
4.	Discussion	38
4.1.	Relative C allocation coefficients for Canadian agroecosystems	38
4.2.	Quantitative estimates of annual C inputs to soil and NPP	39
4.3.	Uncertainty associated with estimates of BNPP	39
5.	Conclusions	41
	Acknowledgement	41
	References	41

1. Introduction

Increases in the concentration of CO₂ in the atmosphere have prompted renewed interest in increasing the stocks of carbon (C) in the world's croplands to mitigate climate change and also improve soil quality (IPCC, 2000; Lal, 2004a,b). To better characterize, predict and manage soil C dynamics, we need more precise and accurate estimates of C inputs to soil. The C fixed in plants by photosynthesis and added to soil as above- and below-ground litter, is the primary source of C in ecosystems (Warembourg and Paul, 1977). Predicting the changes in C stocks (notably in soils), therefore, depends on reliable estimates of net primary productivity (NPP) and the proportion of the NPP returned to the soil (Paustian et al., 1997; Grogan and Matthews, 2002; Bolinder et al., 2006; Campbell et al., 2000; Izaurralde et al., 2001). The concept and definition of NPP varies in the literature. Scurlock and Olson (2002) defined NPP as the increase in plant mass plus losses (such as mortality, herbivory, etc.), summed for both above- and below-ground compartments per unit area of ground per unit of time.

The annual NPP in agroecosystems, and the distribution of C in plant parts, is usually calculated from agricultural yield, the plant component most often measured. In cereal crops, for example, C inputs from post-harvest above-ground residue (i.e., straw) is estimated from grain yields using 'harvest index' values or related regression relationships, and below-ground C inputs are calculated from shoot-to-root (S:R) ratios (Bolinder, 2004; Campbell et al., 2000). While such approaches have been useful, better estimates of crop NPP are needed to adequately assess regional and national contributions of agriculture to the global C budget (Prince et al., 2001).

The largest uncertainty in deriving NPP may originate in estimates of below-ground NPP (BNPP), including inputs from roots, exudates, and other root-derived organic material from root-turnover (root hairs and fine roots that are sloughed during the growing season). Though a large proportion of NPP is allocated to below-ground plant parts (Li et al., 2003; Stanton, 1988), the amount of BNPP is one of the most poorly understood attributes of terrestrial ecosystems (Laurenroth, 2000). Quantifying these below-ground C inputs, notably from exudates and other ephemeral root-derived materials, is difficult and remains a research

priority (Balesdent and Balabane, 1996; Gill et al., 2002; Grogan and Matthews, 2002; Kurz et al., 1996; Kuzyakov and Domanski, 2000).

Our objective was to develop a set of coefficients for estimating total annual NPP, C allocation patterns, and annual C inputs to soil for common agricultural crops in Canada. To do this, we outline a broadly applicable approach for expressing NPP and C allocation in plants, with an emphasis on BNPP, and provide estimates of coefficients, based on a review of the literature, largely from Canadian studies. This approach, using values easily updated, can then be used in modelling efforts to estimate soil C changes in agricultural soils of Canada.

2. Estimates of root biomass in Canadian agroecosystems

We reviewed data from studies with field measurements of shoot and root biomass at or near plant maturity (i.e., harvest), considering only studies published after 1970. Most of the studies were conducted in Canada, though some U.S. studies were included when Canadian data were insufficient and the climate was similar to that in Canada (Tables 1 and 2).

2.1. Description of experiments

The crops in all studies were usually fertilized according to local recommendations, except where the experiment involved fertilizer treatments. Most of the data we used were from studies with conventional experimental designs (i.e., randomized-block, split-plot, split-split-plot and criss-cross) with two to five replicates. Only a few studies involved a field (Soon, 1988; Allmaras et al., 1975), or unreplicated field-plots (Buyanovsky and Wagner, 1986; Kisselle et al., 2001) sub-divided to provide pseudo-replicated experimental units. The number of sub-samples taken for root biomass measurements from each experimental unit (which were subsequently averaged) varied from one to six, but usually one to two sub-samples were taken.

Where possible, we reported or calculated S:R ratios at the treatment level. The data reported for the study by Bowren et al. (1969) on forages (Table 2) were averaged across fertilized and unfertilized treatments (effects were not

Table 1
Shoot to root ratios measured at or close to maturity in field studies for small-grain cereals, corn and soybeans in Canada and the U.S.

Location	Species	Cultivar	Treatment/experiment	Texture	Sampling procedure	Sampling depth (cm)	Shoot/root ratio	Reference
Cooking Lake, Alta.	SW	Roblin	Simulated erosion (0 cm)	NR	Soil cores	40	10.6	Izaurrealde et al. (1992)
			Simulated erosion (20 cm)				4.6	
			Check				4.3	
			Manure Fertilizer				8.6 8.8	
Josephburg, Alta.	SW	Roblin	Simulated erosion (0 cm)	NR	Soil cores	40	11.8	
			Simulated erosion (20 cm)				7.3	
			Check				6.5	
			Manure Fertilizer				10.6 11.6	
Southwestern Saskatchewan	SW	Manitou	Natural rainfall; 0 kg N	L	Lysimeters	120	5.7	Campbell and de Jong (2001)
			Natural rainfall; 20.5 kg N				4.5	
			Natural rainfall; 41 kg N				5.2	
			Natural rainfall; 61.5 kg N				5.5	
			Natural rainfall; 82 kg N				5.6	
			Natural rainfall; 123 kg N				5.9	
			Natural rainfall; 164 kg N				6.0	
			Irrigated; 0 kg N				5.5	
			Irrigated; 20.5 kg N				7.1	
			Irrigated; 41 kg N				6.4	
			Irrigated; 61.5 kg N				6.5	
			Irrigated; 82 kg N				6.5	
			Irrigated; 123 kg N				6.0	
			Irrigated; 164 kg N				6.2	
Ottawa, Ont.	WW	Harus	Recommendation trials	CL	Soil cores	30	4.9	Bolinder et al. (1997)
		AC-Ron	Recommendation trials				4.9	
		Casey	Recommendation trials				4.9	
Quebec, Que.	WW	Borden	Recommendation trials	C	Soil cores	30	7.7	
		Lennox	Recommendation trials				6.8	
		Valor	Recommendation trials				6.5	
Central Missouri (U.S.)	WW	Caldwell	1981 measurement	SiL	Soil cores	50	1.2	Buyanovsky and Wagner (1986)
			1982 measurement				1.1	
			1984 measurement				1.1	
Ellerslie, Alta.	B	Empress	¹⁵ N study	SiCL	Cylinders	30	8.1	Rutherford and Juma (1989)
Breton, Alta.	B		¹⁵ N study	SiL	Cylinders	30	4.8	
Ellerslie, Alta.	B	Abee Samson	¹⁴ C study	SiC	Cylinders	50	17.1	Xu and Juma (1993)
			¹⁴ C study				15.8	
Ellerslie, Alta.	B	Abee	1989 measurement	NR	Soil cores	40	11.8	Xu and Juma (1992)
		Bonanza	1989 measurement				11.5	
		Harrington	1989 measurement				11.3	
		Samson	1989 measurement				10.3	
		Abee	1990 measurement				12.5	
		Bonanza	1990 measurement				10.7	
		Harrington	1990 measurement				10.4	
Samson	1990 measurement	9.4						
Ellerslie, Alta.	B	Empress	Conventional tillage	SiCL	Cylinders	30	11.9	Haugen-Kozyra et al. (1993)
			Zero tillage				13.4	

Table 1 (Continued)

Location	Species	Cultivar	Treatment/experiment	Texture	Sampling procedure	Sampling depth (cm)	Shoot/root ratio	Reference
Ellerslie, Alta.	B	NR	Diverse cropping systems	SiL	Soil cores	40	8.3	Izaurralde et al. (1993)
Breton, Alta.	B	NR	Diverse cropping systems	L			8.3	
Beaverlodge, Alta.	B	Galt	Spatial distribution study	SiL	Soil cores	90	6.7	Soon (1988)
Ottawa, Ont.	B	Leger	Recommendation trials	CL	Soil cores	30	2.0	Bolinder et al. (1997)
		Chapais	Recommendation trials				1.7	
		Codac	Recommendation trials				2.3	
Ottawa, Ont.	O	Ultima	Recommendation trials	CL	Soil cores	30	2.4	Bolinder et al. (1997)
		Lotta	Recommendation trials				2.5	
		Rigodon	Recommendation trials				2.7	
Quebec, Que.	T	Wintri	Recommendation trials	C	Soil cores	30	5.1	Bolinder et al. (1997)
		Trillium	Recommendation trials				5.6	
Kansas (U.S.)	GS	Moench	Hybrid and backcross study	SiL	Excavated	NR	11.6	Piper and Kulakow (1994)
Saint-Hyacinthe, Que.	GC	Pride	¹⁵ N study	SL, CL	Excavation	25	11.2	Tran and Giroux (1998)
Saint-Lambert, Que.	SC	Hyland	¹⁵ N study	SiL, SL			10.0	
Montreal, Que.	GC	Pioneer	Low fertility site	FSL	Soil cores	60	8.1	Zan et al. (2001)
	GC	Pioneer	High fertility site				8.5	
Southwestern Missouri (U.S.)	GC	DeKalb	Water relationships study	SC	Excavation	152	5.7	Allmaras et al. (1975)
Mead, NE (U.S.)	GC	Four genotypes	0 kg N	SiCL	Soil cores	90	5.2	Eghball and Maranville (1993)
			60 kg N				6.3	
			120 kg N				7.8	
			180 kg N				6.9	
			Dryland				5.6	
			Irrigated				7.5	
Clarksville, MD (U.S.)	GC	Pioneer	1982: 0 kg N	SL	Soil cores	60	3.9	Anderson (1988)
			1982: 180 kg N				6.7	
			1983: 0 kg N				2.5	
			1983: 180 kg N				4.8	
			1984: 0 kg N				2.6	
			1984: 180 kg N				5.6	
Central Missouri (U.S.)	GC	Pioneer	1981 measurement	SiL	Soil cores	50	1.4	Buyanovsky and Wagner (1986)
			1982 measurement				0.9	
Horseshoe Bend, GA (U.S.)	GC	NR	Conventional tillage	NR	Soil cores	15	2.8	Kisselle et al. (2001)
			No-tillage				3.2	
Fayetteville, AR (U.S.)	SYBN	Forrest	Root competition	SiL	Cylinder	20	8.0	Marvel et al. (1992)
			No root competition				8.0	
Southwestern Missouri (U.S.)	SYBN	Harosoy (D)	Water relationships study	SC	Excavated	152	7.0	Allmaras et al. (1975)
		Harosoy (I)					5.3	
Central Missouri (U.S.)	SYBN	Merrill	1981 measurement	SiL	Soil cores	50	1.8	Buyanovsky and Wagner (1986)
			1982 measurement				1.2	
			1983 measurement				0.9	
			1984 measurement				1.0	
Ashland, KS (U.S.)	SYBN	Williams	Irrigated	SiL	Excavated	180	8.1	Mayaki et al. (1976)
			Non irrigated				4.8	
Horseshoe Bend, GA (U.S.)	SYBN	Bragg	Conventionally tilled	L	Excavated	30	8.0	House et al. (1984)
			No-tilled				7.9	

Species: SW, spring wheat; WW, winter wheat; B, barley; O, oats; T, triticale; GS, grain–sorghum; GC, grain–corn; SC, silage–corn; SYBN, soybeans. Textural class: F, fine; S, sand; L, loam; C, clay; Si, silt.

significant) and across sites. The forage data from Kunelius et al. (1992) are averages from five small-plot experiments over 3 years, and the data for corn (*Zea mays* L.) (Table 1) from Eghball and Maranville (1993) are averages for four hybrids.

2.2. Sampling procedures and methods for root separation

Procedures used to sample roots in these field experiments included extraction of soil cores, excavation

Table 2
Shoot to root ratios measured at or close to maturity in field studies for cultivated forages in Canada and the U.S

Location	Species	Cultivar	Treatment/experiment (growth stage)	Texture	Sampling procedure	Sampling depth (cm)	Shoot/root ratio	Reference
Ellerslie, Alta.	F (Grass sp.)	Creeping red	(1st PY)	SiL	Soil cores	40	1.3	Izaurrealde et al. (1993)
Breton, Alta.				L			0.9	
Melfort, Sask.	SC (Leg sp.) A (Leg sp.) RC (Leg sp.)	Erector Ladak Altaswede	Fertilized and unfertilized combined (2nd, 3rd, and 4th PY combined)	SiC	Excavated	20	4.1 1.2 3.1	Bowren et al. (1969)
White fox, Sask.	SC (Leg sp.) A (Leg sp.) RC (Leg sp.)	Erector Ladak Altaswede		FSL			4.8 1.9 3.2	
Swift current, Sask.	BG (Grass sp.)	Leys.	0 kg N (ES, 20 years) 50 kg N (ES, 20 years) 100 kg N (ES, 20 years) 200 kg N (ES, 20 years)	SiC to CL	Soil cores	90	0.3 0.4 0.7 0.8	Leyshon (1991)
Outlook, Sask.	BG (Grass sp.) BG (Mix.) A (Leg sp.) A (Mix.)	Fleat Fleat Beaver Beaver	Monocropped (EYPS) Monocropped (1st PY) Monocropped (2nd PY) Intercropped (EYPS) Intercropped (1st PY) Intercropped (2nd PY) Monocropped (EYPS) Monocropped (1st PY) Monocropped (2nd PY) Intercropped (EYPS) Intercropped (1st PY) Intercropped (2nd PY)	SL	Excavated	30	0.2 0.4 0.1 0.5 0.5 0.3 0.4 0.7 0.7 0.7 1.0 1.0	Walley et al. (1996)
Montreal, Que.	SG (Grass sp.)	Cave-In-Rock	Low fertility site (3rd PY) High fertility site (3rd PY)	FSL	Soil cores	60	1.7 2.6	Zan et al. (2001)
PEI	IR (Grass sp.) WR (Grass sp.) RC (Leg sp.)	Lemtal Aubade Flores	Small plot study (EYPS) Small plot study (EYPS) Small plot study (EYPS)	FSL	Excavated	18	2.9 4.4 2.3	Kunelius et al. (1992)
Charlottetown, PEI	IR (Grass sp.) RC (Leg sp.)	Lemtal Flores	1987 measurement (EYPS) 1988 measurement (EYPS) 1989 measurement (EYPS) 1990 measurement (EYPS) 1991 measurement (EYPS) 1992 measurement (EYPS) 1993 measurement (EYPS) 1994 measurement (EYPS) 1987 measurement (EYPS) 1988 measurement (EYPS) 1989 measurement (EYPS) 1990 measurement (EYPS) 1991 measurement (EYPS) 1992 measurement (EYPS) 1993 measurement (EYPS) 1994 measurement (EYPS)	FSL	Excavated	18	1.3 1.2 0.8 0.8 2.5 3.9 2.2 2.3 1.7 2.2 1.6 4.2 2.7 2.4 3.8 3.5	Carter et al. (2003)
Fredericton, NB	OG (Grass sp.) F (Grass sp.) BG (Grass sp.) CG (Grass sp.) T (Grass sp.) R (Grass sp.) SG (Grass sp.) RC (Leg sp.) A (Leg sp.)	Kay NR Radisson Palaton Champ Riika Trailblazer Flores Apica	1995 measurement (1st PY) 1995 measurement (1st PY) 1995 measurement (1st PY) 1995 measurement (1st PY) 1995 measurement (1st PY) 1995 measurement (1st PY) 1995 measurement (1st PY) 1995 measurement (1st PY)	FSL	Soil cores	45	1.3 1.6 1.7 1.0 1.2 1.5 1.2 1.0 1.4	Bolinder et al. (2002)

Table 2 (Continued)

Location	Species	Cultivar	Treatment/experiment (growth stage)	Texture	Sampling procedure	Sampling depth (cm)	Shoot/root ratio	Reference
Fredericton, NB	OG (Grass sp.)	Kay	1996 measurement (2nd PY)	FSL	Soil cores	45	0.7	Bolinder et al. (2002)
	F (Grass sp.)	NR	1996 measurement (2nd PY)				0.5	
	BG (Grass sp.)	Radisson	1996 measurement (2nd PY)				0.8	
	CG (Grass sp.)	Palaton	1996 measurement (2nd PY)				0.5	
	T (Grass sp.)	Champ	1996 measurement (2nd PY)				0.5	
	R (Grass sp.)	Riika	1996 measurement (2nd PY)				0.4	
	SG (Grass sp.)	Trailblazer	1996 measurement (2nd PY)				0.5	
	RC (Leg sp.)	Florex	1996 measurement (2nd PY)				0.8	
	A (Leg sp.)	Apica	1996 measurement (2nd PY)				0.9	
Rosemount, MN (U.S.)	A (Leg sp.)	Answer	(EYPS, 1st PY and	SiL	Excavated	30	1.4	Sheaffer et al. (1991)
	RC (Leg sp.)	Florex	2nd PY combined)				1.2	
	BT (Leg sp.)	Leo					1.1	
PEI	IR (Grass sp.)	Lemtal	Small plot study (EYUS)	SL	Excavation	18	2.3	Kunelius et al. (1992)
	IR (Grass sp.)	Barmultra	Small plot study (EYUS)				1.2	
	WR (Grass sp.)	Aubade	Small plot study (EYUS)				2.3	
	WR (Grass sp.)	Marshall	Small plot study (EYUS)				4.8	
	RC (Leg sp.)	Florex	Small plot study (EYUS)				4.6	
	IR (Grass sp.)	Lemtal	Large plot study (EYUS)				2.4	
	IR (Grass sp.)	Barmultra	Large plot study (EYUS)				2.7	
	WR (Grass sp.)	Aubade	Large plot study (EYUS)				2.3	
	WR (Grass sp.)	Marshall	Large plot study (EYUS)				5.0	
	RC (Leg sp.)	Florex	Large plot study (EYUS)				3.7	

Species: F, fescue; SC, sweet clover; A, alfalfa; RC, red clover; BG, bromegrass; SG, switchgrass; IR, Italian ryegrass; WR, esterwolds ryegrass; OG, orchardgrass; CG, canarygrass; T, timothy; R, ryegrass; BT, birdsfoot trefoil (Grass sp., grass species; Leg sp., legume species; Mix., mixture of grass and legume species). Growth stage: EYPS, establishment year pure seeded; EYUS, establishment year under-seeded; PY, production year (years (s) after establishment); ES, established stand. Textural class: F, fine; S, sand; L, loam; C, clay; Si, silt.

techniques which involved removal of sections or blocks of soils of varying sizes (e.g., 20 cm × 30 cm, 30 cm × 70 cm, and 100 cm × 75 cm), and, in one case, lysimeters. Piper and Kulakow (1994), in a grain–sorghum (*Sorghum bicolor*) cropping system (Table 1) used an excavation procedure involving the removal of entire plants. Most estimates of root biomass were made on light-textured soils (i.e., <40% clay). The methods for sampling roots in the field have been described by Böhm (1979).

Samples were usually obtained at random positions in forage crops, but for row crops, the sampling patterns varied. Bolinder et al. (1997) averaged measurements from three different positions: within the row, between the rows, and in an intermediate position between these positions. In some other studies, samples were taken from two positions – in the row and between the rows (Buyanovsky and Wagner, 1986; Eghball and Maranville, 1993; Soon, 1988; Xu and Juma, 1992) – and the results were averaged. Some differences in S:R ratios among studies may reflect different sampling methods used (Van Noordwijk et al., 1985).

All studies using soil cores separated the roots from the root–soil mixture with water. Five of these studies (Izaurrealde et al., 1992, 1993; Bolinder et al., 1997, 2002; Xu and Juma, 1992) used a hydropneumatic elutriation system (Smucker et al., 1982). A washing procedure was also used in the lysimeter study and in

some excavation studies (Kunelius et al., 1992; Walley et al., 1996; Carter et al., 2003; Piper and Kulakow, 1994; Allmaras et al., 1975; Mayaki et al., 1976; House et al., 1984). In three studies using cylinders (Rutherford and Juma, 1989; Xu and Juma, 1993; Haugen-Kozyra et al., 1993) roots were manually separated from the soil, but washing was not specified. In the remaining four studies, the method of root separation was not specified. The sieve sizes used to separate roots from the root–soil mixture by washing, specified in 10 of 27 studies, varied from 0.25 to 2 mm, but was usually between 0.25 and 0.5 mm. Root recovery is influenced by sieve size (Amato and Pardo, 1994), but the optimal size often varies with soil texture.

2.3. Shoot-to-root ratios and sampling depth

Root samples were usually dried to constant weight and expressed on a dry matter basis. In some studies, these weights were further corrected for potential soil-contamination by dry-ashing (Bolinder et al., 2002; Leyshon, 1991; Kisselle et al., 2001).

The sampling depth for measuring root biomass varied from 18 to 180 cm (Tables 1 and 2), but usually (128 out of 168 site-treatment combinations) did not exceed 45–50 cm. Root biomass in the upper 30 cm accounted for 95% of the total recovered to the sampled depth (40–50 cm) for small-grain cereals in three studies (Buyanovsky and Wagner,

1986; Izaurralde et al., 1993; Xu and Juma, 1993), but for only 60% in the study by Campbell and de Jong (2001) who sampled to a depth of 120 cm. For corn and soybeans (*Glycine max*), root biomass in the upper 30 cm represented 95% of root biomass to a depth of 50 cm (Buyanovsky and Wagner, 1986). For forages, Leyshon (1991) determined that 65% of the roots to a depth of 90 cm were in the upper 30 cm, and Bolinder et al. (2002) reported that the proportion of roots in the deepest sampling layer (i.e., 30–45 cm) remained constant at 10% during 2 years of measurement. These distributions are similar to those for mixed prairies of the northern Great Plains reported by Lorenz (1977), who found that the upper 30 cm accounted for 77% ($n = 38$) of roots to a depth of 122 or 152 cm.

Shoot-to-root ratios were calculated using the total amounts of roots recovered in the various studies (Tables 1 and 2). For forage crops, the ‘shoot’ in this ratio was calculated using the total biomass measured in all harvests during the growing season (from one to four cuts per season). Shoot and root data were expressed on a dry matter basis; for studies that reported dry matter on both total and ash-free basis, we used the latter. To calculate S:R ratios, we assumed complete root recovery in all of the studies, recognizing that some differences existed in sampling protocols among studies. For annual crops, S:R ratios were calculated from biomass measured at plant maturity. In perennial forages the root biomass and S:R ratios may vary with age of the stand (Weaver and Zink, 1946; Troughton, 1957; Hansson and Andrén, 1986) and the equilibrium between net root growth and root turnover may not be reached until 2–4 years after establishment (Troughton, 1957). Root biomass generally increases between the 1st and 2nd production year, typically by about 50% (Hansson and Andrén, 1986; Pettersson et al., 1986), but this increase can be much higher for some species (Bolinder et al., 2002). Therefore, we assessed the forage S:R ratios by growth stage (e.g., establishment year pure seeded, and 1 and 2 year after establishment).

3. Proposed method for estimating total annual NPP, C allocation, and C input to soil

3.1. NPP and C allocation

We propose a method for describing the accumulation and distribution of C in crop plants. The criteria for this method are:

1. It should include all plant C fractions. The sum of these fractions should be a reasonable approximation of NPP for agroecosystems, and allow direct comparison with NPP of other ecosystems.
2. Its plant C fractions should be compatible with readily available data, particularly with yield data widely available for most agricultural crops.

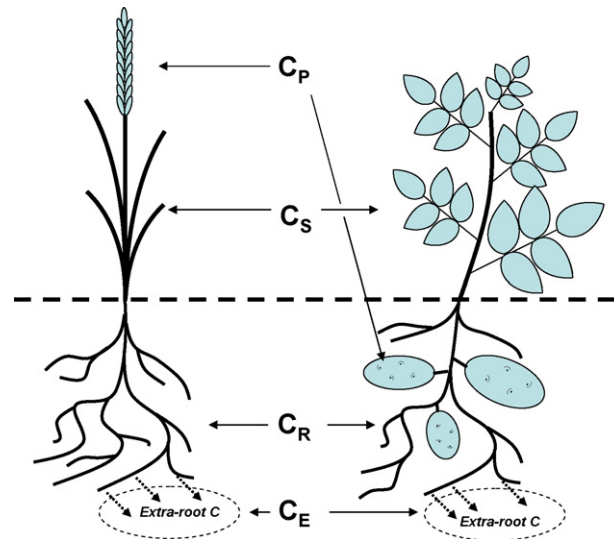


Fig. 1. An illustration, for two conceptualized plants, of the proposed C pools, for quantifying annual C allocation in crop plants. C_P = C in ‘product’ (e.g., grain, forage, tuber); C_S = C in above-ground residue (e.g., straw, stover, chaff); C_R = C in roots (not including that fraction designated as ‘product’); C_E = extra-root C (including all root-derived materials not usually recovered in the ‘root’ fraction). For forage crops (not shown), C_P is C in all above-ground plant parts (i.e., $C_S = 0$).

3. It should allow direct and easy estimation of annual C inputs to soil, for use in models of soil C dynamics in response to crop type and management practices.

To meet these criteria, we apportioned the C in crop plants into four fractions, expressed in units of mass C per unit area per unit of time (e.g., $\text{g C m}^{-2} \text{yr}^{-1}$) (Fig. 1):

- C_P plant C in the agricultural product, the plant portion of primary economic value, and typically harvested and exported from the ecosystem. The ‘product’ can be either above-ground (e.g., grain, hay) or below-ground (e.g., tuber). For forage crops, all exported above-ground plant material is considered ‘product’.
- C_S plant C in straw, stover and other above-ground post-harvest residue. This fraction includes all above-ground plant materials excluding the ‘product’.
- C_R plant C in root tissue, comprised of all below-ground, physically recoverable plant materials, excluding any ‘product’.
- C_E plant C in extra-root material, including root exudates and other material derived from root-turnover, not easily recovered by physically collecting, sieving or removal. This fraction is roughly equivalent to that sometimes referred to as ‘rhizodeposition’.

Now:

$$\text{NPP} = C_P + C_S + C_R + C_E \quad (1)$$

The amount of C in each of these four fractions (and thus also NPP) can be estimated from agricultural yields, using published or assumed values for harvest index (HI), S:R ratios, plant C in root exudates, and C concentrations in the

plant parts. In a grain crop, for example, assuming the C concentration of all plant parts is 0.45 g g^{-1} :

$$C_P = Y_P \times 0.45 \quad (2)$$

$$C_S = Y_P(1 - \text{HI})/\text{HI} \times 0.45 \quad (3)$$

$$C_R = Y_P/(S : R \times \text{HI}) \times 0.45 \quad (4)$$

$$C_E = C_R \times Y_E \quad (5)$$

where Y_P is the dry matter yield of above-ground product ($\text{g m}^{-2} \text{ yr}^{-1}$), HI the harvest index = dry matter yield of grain/total above-ground dry matter yield, S:R the shoot:root ratio, and Y_E is the extra-root C (rhizodeposit C), expressed as factor relative to recoverable roots.

For perennial crops, root C persists from year to year. Hence, C_R is defined as the *increase* in root C in the year it was established. Therefore, C_R for perennial forage crops is only included in NPP in the year of establishment. (This assumes that C_R does not increase after year 1.)

The allocation of C within different crop plant parts can also be expressed using relative C allocation coefficients, essentially an expansion of HI, expressed as a proportion of NPP:

$$R_P = C_P/\text{NPP} \quad (6)$$

$$R_S = C_S/\text{NPP} \quad (7)$$

$$R_R = C_R/\text{NPP} \quad (8)$$

$$R_E = C_E/\text{NPP} \quad (9)$$

By definition:

$$R_P + R_S + R_R + R_E = 1 \quad (10)$$

These C allocation coefficients can be readily used to calculate the corresponding value of C_P , C_S , C_R , and C_E , if one of these (typically C_P) is known:

$$C_S = (R_S/R_P) \times C_P \quad (11)$$

$$C_R = (R_R/R_P) \times C_P \quad (12)$$

$$C_E = (R_E/R_P) \times C_P \quad (13)$$

3.2. Annual C inputs to soil

In the simplest case, if only the ‘product’ is harvested, the amount of C added to soil is estimated as: $\text{NPP} - C_P$. Often, however, only a portion of some fractions is returned to the soil. To account for that, we introduce an additional parameter, S , which describes the proportion of the C in a given fraction that is returned to soil. Typically, by default: $S_P = 0$, $S_S = 1$, $S_R = 1$, and $S_E = 1$ (where S_P , S_S , S_R , and S_E are the proportions of C in product, above-ground residue, roots, and extra-root C, respectively, that are returned to soil). If a portion of a fraction is removed (e.g., wheat straw removed for feed or bedding), then $S_S < 1$. Thus:

$$C_i = [C_P \times S_P] + [C_S \times S_S] + [C_R \times S_R] + [C_E \times S_E] \quad (14)$$

where C_i is the annual C input to soil.

In perennial forage crops, only a portion of the above-ground vegetation is removed by grazing or harvest, hence $S_P < 1$. As well, there may be significant litter fall and harvest losses, typically about 15% (e.g., [Tomm et al., 1995](#)), but these can be reflected and adjusted in the S_P factor. Since roots persist from year to year for perennial forage crops, $S_R = 0$, except when the crop is discontinued (i.e., then $S_R = 1$).

Relative C input (R_i), expressing C input to soil as a proportion of NPP, is calculated as

$$R_i = C_i/(C_P + C_S + C_R + C_E) \quad (15)$$

3.3. Assumptions used in calculations

3.3.1. Harvest index

Harvest index values were estimated from studies across Canada using the definition of [Donald \(1962\)](#), where grain yield is expressed as a proportion of total above-ground biomass on a dry weight basis. Thus:

$$\text{HI} = Y_P/(Y_P + Y_S) \quad (16)$$

Estimated HI values for annual crops ([Table 5](#)) ranged from a low of 0.25 for grain–sorghum to 0.63 for under-seeded barley.

3.3.2. Shoot:root ratios

The mean S:R ratios for annual crops were typically about 5, though values ranged from 1.1 to 10.7 ([Table 3](#)). There were few consistent regional differences, except for barley (*Hordeum vulgare* L.), which had a much lower S:R ratio in eastern Canadian studies (2.0) than in western Canadian studies (10.7). This difference may be attributable to the effects of climate and varieties, or it may reflect, in part, different approaches used in the extraction and measurement of root biomass. Average S:R ratio in corn (5.6) was similar to that of soybeans (5.2). The estimated S:R ratio for corn in eastern Canada was higher than that in the U.S. studies. Fertilization appears to have increased the S:R ratio. The mean coefficient of variation (CV) for these location-treatment combinations by crop type was approximately 50% (e.g., 49% for small-grain cereals, 42% for under-seeded small-grain cereals, 50% for corn, and 60% for soybeans).

The mean S:R ratio of forages ([Table 4](#)) was typically 1–2, much lower than that of annual crops. The S:R ratio for legume species was nearly twice that of grass species. In eastern Canada, the S:R ratio appeared to decrease with the age of the stand, but this trend was not observed in western Canada. The mean CV for forages was 75% (i.e., 77% for grass species, 59% for legume species and 43% for mixtures of the two), higher than that for the cereals and soybeans. The higher variation in forage measurements may partly reflect the difficulty in accurately sampling the dense and diffuse root system of forages.

The Canadian data for forages were mostly from short-term rotations (i.e., establishment year or first 4 production years). Only the measurements by [Leysdon \(1991\)](#) were from a long-term stand (i.e., 20 years); the mean S:R ratio for

Table 3
Summary and associated variability in measurements of shoot to root ratios for small-grain cereals, corn and soybeans

		Shoot/root ratio ^a	n for shoot/root ratio
Small-grain cereals	All studies	7.4 ± 3.6	59
	Western Canada	8.5 ± 3.2	41
	Eastern Canada	4.3 ± 2.0	14
Spring wheat	Western Canada	7.0 ± 2.2	24
	Fertilized	5.6 ± 0.1	22
	Unfertilized	7.1 ± 2.3	2
Winter wheat	Eastern Canada	6.0 ± 1.2	6
Winter wheat	U.S.	1.1 ± 0.1	3
Barley	Western Canada	10.7 ± 3.1	17
	Eastern Canada	2.0 ± 0.3	3
Oats	Eastern Canada	2.5 ± 0.2	3
Triticale	Eastern Canada	5.4 ± 0.4	2
Grain–sorghum	U.S.	11.6	1
Under-seeded small-grain cereals			
Barley	Eastern Canada	3.1 ± 1.3	10
Barley (Graminuous)		2.9 ± 1.3	8
Barley (Leguminuous)		4.2 ± 0.6	2
Corn (grain and silage)			
	All studies	5.6 ± 2.8	21
	Eastern Canada	9.5 ± 1.4	4
	U.S.		
	Fertilized	4.7 ± 2.1	17
	Unfertilized	3.6 ± 1.3	4
Soybeans	All studies (U.S.)	5.2 ± 3.1	12

^a Mean ± S.D.

Table 4
Summary and associated variability in measurements of shoot to root ratios for cultivated forages

		Shoot/root ratio ^a	n for shoot/root ratio
Forages	All studies ^b	1.6 ± 1.2	63
	Western Canada	1.2 ± 1.3	24
	Eastern Canada	1.8 ± 1.1	39
Grass species	All studies	1.3 ± 1.0	35
	Western Canada	0.6 ± 0.4	9
	Eastern Canada	1.5 ± 1.1	26
EYPS ^c	Western Canada	0.2	1
1st PY ^d		0.9 ± 0.5	3
2nd PY		0.1	1
EYPS	Eastern Canada	2.2 ± 1.3	10
1st PY		1.4 ± 0.3	7
2nd PY		0.6 ± 0.1	7
Legume species	All studies	2.2 ± 1.3	22
	Western Canada	2.2 ± 1.6	9
	Eastern Canada	2.2 ± 1.1	13
EYPS	Western Canada	0.4	1
1st PY		0.7	1
2nd PY		0.7	1
EYPS	Eastern Canada	2.7 ± 0.9	9
1st PY		1.2 ± 0.3	2
2nd PY		0.9 ± 0.1	2
Mixture	All studies	0.7 ± 0.3	6
EYPS	Western Canada	0.6 ± 0.1	2
1st PY		0.8 ± 0.4	2
2nd PY		0.7 ± 0.5	2

^a Mean ± S.D.

^b Excluding the U.S. data.

^c EYPS: establishment year pure seeded.

^d PY: production year (i.e., years after establishment).

that study was 0.6, with a range of 0.3–0.7 (Tables 2 and 4). Stanton (1988) showed that S:R ratios for U.S. grasslands varied from 0.1 to 0.5, with the lower values for cooler climates. Bolinder et al. (2002) found that S:R ratios for natural grasslands were between 0.2 and 1.8, but several studies reported values near 0.5. Based on these findings, we conclude that a S:R ratio of 0.5 is appropriate for long-term prairie grasslands and pasture ecosystems in Canada.

3.3.3. Extra-root C

The plant C in root tissue at harvest (C_R) is not the only contribution from below-ground plant components to NPP and annual C inputs. A significant, though poorly quantified, proportion of NPP is released into the soil from the extra-root (rhizodeposit) component (C_E). This material includes exudates, as well as root hairs and fine roots sloughed off during the growing season which, because of sampling difficulties, are not included in the ‘root’ fraction.

Recent reviews of tracer studies indicates that roughly 33% of C allocated below-ground in wheat and barley is

released by living roots and remains in soil (including in the soil microbial biomass), and that 50% of below-ground C remains in roots (Kuzyakov and Domanski, 2000; Kuzyakov and Schneckenberger, 2004). This implies that $C_E \sim 0.65$ (i.e., $33/50$) $\times C_R$, but values varied widely among studies. As a preliminary estimate for small-grain cereals, corn, and soybean, we assume, that $C_E = 0.65 \times C_R$. This estimate is more conservative than those presented in earlier studies. For example, some studies of annual crops (corn and small-grain cereals) assumed that extra-root C (rhizodeposited C) is equal to root C; that is: $C_E = C_R$ (Barber, 1979; Bolinder et al., 1997, 1999; Plénet et al., 1993), based on studies by Barber and Martin (1976) and Sauerbeck and Johnen (1977).

Most studies of C from rhizodeposition in perennial forages have considered only pastures and natural grasslands. In reviewing the literature on root C inputs, Kuzyakov and Domanski (2000) concluded that the rhizodeposition in pastures was comparable to that in small-grain cereals (i.e., $C_E = 0.65 \times C_R$). Gill et al. (2002) concluded that in natural grasslands about 65% of roots die and detach every year.

Thus, for perennial forages, we also assume that $C_E = 0.65 \times C_R$.

Our estimates of extra-root C have high uncertainty reflecting the variability of measured values. Nevertheless, we present these estimates as a first approximation, recognizing that more reliable estimates emerging from further research can be easily incorporated into our approach.

4. Discussion

4.1. Relative C allocation coefficients for Canadian agroecosystems

The relative C allocation coefficients (R_P , R_S , R_R , R_E) and relative C input (R_i), which expresses C input as a proportion of NPP, were calculated for a range of crops under Canadian

conditions (Tables 5 and 6). For small-grain cereals (Table 5), we estimated a range of R_i values, spanning full removal to full retention of above-ground residues. For perennial forage crops (Table 6), the minimum value for R_i represents the C input from a forage crop that is continued, and the maximum value is that for a forage crop that is discontinued. Because there were few consistent differences in S:R ratios between regions (Tables 3 and 4), we calculated mean values for the country. The R_R value we used for forages (Table 6) was estimated from the average of the S:R ratios (Table 4) from the studies where forages were grown in short-term rotations (i.e., in the establishment year or 1st production years).

Our estimates of maximum R_i (where all residues are returned to soil) ranged from 0.55 to 0.78 for annual crops (Table 5). Estimates of minimum R_i values for small-grain cereals (where all manageable residues are removed) ranged

Table 5
Relative annual plant C allocation coefficients for small-grain cereals, grain–corn and soybeans used to estimate NPP and C input to soil for Canadian agroecosystems

Crop type	HI ^a (%)	Relative plant C allocation coefficients				Relative proportion (R_i) of NPP returned to soil ^b
		R_P	R_S	R_R	R_E	
Small-grain cereals	41	0.335	0.482	0.110	0.073	0.26–0.67
Wheat ^c	40	0.322	0.482	0.118	0.078	0.27–0.68
Barley	53	0.451	0.400	0.090	0.059	0.21–0.55
Oats	53	0.319	0.283	0.241	0.157	0.44–0.68
Triticale	34	0.260	0.506	0.142	0.092	0.31–0.74
Grain–sorghum	25	0.219	0.656	0.075	0.050	0.22–0.78
Under-seeded small-grain cereals						
Barley	63	0.411	0.241	0.211	0.137	0.38
Grain–corn	50	0.386	0.387	0.138	0.089	0.27–0.61
Soybeans	40	0.304	0.455	0.146	0.095	0.29–0.70

Relative plant C allocation coefficients : $R_P = C_P/NPP$, $R_S = C_S/NPP$, $R_R = C_R/NPP$, $R_E = C_E/NPP$ (see the text).

^a Sources: Izaurre et al. (2001), Campbell and Zentner (1993), Bolinder et al. (1997, 1999), Kunelius et al. (1992), Piper and Kulakow (1994), Buyanovsky and Wagner (1986) and Schapaugh and Wilcox (1980).

^b The minimum of the range specified assumes all recoverable above-ground material is exported (calculated with $S_S = 0.15$ for small-grain cereals and 0.10 for grain–corn and soybeans; representing the proportion of above-ground plant parts returned to the soil as stubble and other surface debris); the maximum assumes all material, except for plant products are returned to the soil.

^c Only the Canadian data for S:R were used.

Table 6
Relative annual plant C allocation coefficients for perennial forage crops and silage–corn used to estimate NPP and C input to soil for Canadian agroecosystems

Crop type	Relative plant C allocation coefficients				Relative proportion (R_i) of NPP returned to soil ^a
	R_P	R_S	R_R	R_E	
Perennial forages	0.492	0.000	0.308	0.200	0.27–0.63
Grass species	0.441	0.000	0.339	0.220	0.29–0.67
Legume species	0.571	0.000	0.260	0.169	0.26–0.57
Mixture	0.298	0.000	0.426	0.277	0.32–0.78
Grassland/pasture	0.233	0.000	0.465	0.302	0.34
Silage–corn ^b	0.772	0.000	0.138	0.090	0.27

^a The minimum value represents calculations for a forage crop that is not discontinued; the maximum value assumes that the perennial forage crops would have been discontinued (see the text). For a continuous forage crop we considered that the harvested hay represented 85% of the total above-ground production ($S_P = 0.15$; representing the proportion of above-ground plant parts returned to the soil as litter fall and harvest losses) and that it represented 75% ($S_P = 0.25$) when it is discontinued (i.e., at that time an additional 10% is left behind in the field as stubble). For silage–corn we assumed that 95% of the above-ground biomass was removed ($S_P = 0.05$).

^b We used the same shoot to root ratio for both grain– and silage–corn.

from 0.21 to 0.44. The relative proportion of NPP returned to soil for perennial forage (Table 6), depends on whether this crop is continued or discontinued. The R_i for perennial forages (continued), silage–corn, and grassland/pasture was about 0.30. In the year of termination, forage crops had much higher R_i values (0.57–0.78), similar to the maximum R_i for annual crops.

The proportion of NPP as BNPP (i.e., $R_R + R_E$) (Tables 5 and 6) was, on average, 18% for small-grain cereals, 23% for corn, 24% for soybeans, and 51% for perennial forages (in the year of establishment). These values are slightly lower than those of natural ecosystems: 48–64% for a tallgrass prairie, 70–78% in a shortgrass prairie and 61–80% of NPP for a mixed-grassland ecosystem (Stanton, 1988). For forest ecosystems, Li et al. (2003) reviewed above- and below-ground data in the literature for softwood ($n = 340$) and hardwood ($n = 103$) species grown on the Canadian Prairie Provinces. They found that BNPP as a proportion of NPP was 55% for subarctic, 46% for boreal forests, 43% for grassland and 48% for cordilleran forests. On average, for the entire region, the BNPP estimate for forests represented 47% of total NPP, lower than in an earlier estimate (Kurze et al., 1996). Our findings suggest that relative BNPP allocation in perennial forage crops in Canada is comparable to that in Canadian forest ecosystems.

4.2. Quantitative estimates of annual C inputs to soil and NPP

Although comparing relative C allocation patterns among different Canadian agroecosystems is useful, for modelling soil C changes in agricultural soils we need to estimate the actual amount of C inputs (C_i) entering the soil. Indeed, C input is one of the most important driving variables for predicting the net rate of soil C change (Bolinder et al., 2006).

To illustrate the variability in estimates of C inputs for crops in Canadian agroecosystems, we used the proposed method to calculate C_i for small-grain cereals and perennial forages. We assumed a grain yield of 4 Mg DM ha⁻¹ (i.e., $C_P = 180$ g C m⁻²) and a total annual hay yield of 8 Mg DM ha⁻¹ (i.e., $C_P = 360$ g C m⁻²), values typical of eastern Canadian farms.

Using Eqs. (11)–(13) for small-grain cereals and coefficients from Table 5:

$$C_S = (0.482/0.335) \times 180 = 259 \text{ g C m}^{-2},$$

$$C_R = (0.110/0.335) \times 180 = 59 \text{ g C m}^{-2},$$

$$C_E = (0.073/0.335) \times 180 = 39 \text{ g C m}^{-2}$$

From Eq. (14), if all residue is returned to soil:

$$\begin{aligned} C_i &= [180 \times 0] + [259 \times 1] + [59 \times 1] + [39 \times 1] \\ &= 357 \text{ g C m}^{-2} \end{aligned}$$

And if residues are removed:

$$\begin{aligned} C_i &= [180 \times 0] + [259 \times 0.15] + [59 \times 1] + [39 \times 1] \\ &= 137 \text{ g C m}^{-2} \end{aligned}$$

In the same manner, using Eqs. (11)–(14) generates estimates of $C_i = 462$ g C m⁻² if the forage crop is discontinued, but only $C_i = 200$ g C m⁻² if it is continued. This example shows the key role of management on C inputs, and illustrates how decisions about straw removal or duration of forage crop stands may affect the C input as much (or more than) the type of crop grown.

We also used the proposed method to compare estimates of NPP for agroecosystems with those of forest ecosystems (Fig. 2), using data from Li et al. (2003), who calculated NPP for boreal forests in Manitoba, Saskatchewan and Alberta with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2). Their model estimates were compared to average NPP estimates we calculated (Eqs. (1), (11)–(13)) for some annual agricultural crops in the same provinces and time-period (1991–1995) using average yield data from Statistics Canada. The results showed that the average NPP of annual crops was slightly higher than that for boreal forests (though, admittedly, climate and soils are not directly comparable for the two biomes). In this example, highest NPP for both boreal forests and annual crops was in Alberta.

4.3. Uncertainty associated with estimates of BNPP

There is substantial uncertainty in the estimates of BNPP and, as a consequence, the C inputs derived from those estimates. The mean CV for S:R ratios was as high as 50% for annual crops (Table 3) and 75% for perennial forages (Table 4). However, this uncertainty in estimates of BNPP is common also in other ecosystems. For example, Williams et al. (2005) estimated that the error for fine root biomass for a

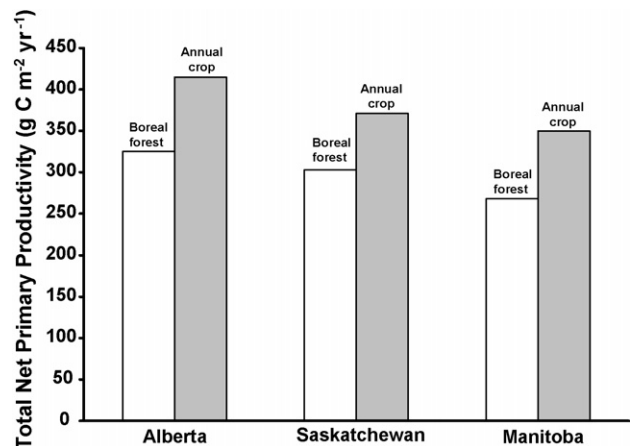


Fig. 2. Comparison between total net primary productivity estimated for boreal forests with the CBM–CFS2 model (data from Li et al. (2003)) and that of the average estimated with the proposed method for some annual crops (grain–corn, soybeans and small-grain cereals) commonly grown in Canadian prairie agroecosystems for the period 1991–1995.

ponderosa pine stand in Oregon (U.S.) was $\pm 30\%$. Furthermore, Cairns et al. (1997) compiled worldwide literature estimates for broadleaf ($n = 102$) and coniferous ($n = 63$) forests and reported that the coefficient of variation of S:R ratios varied between 27 and 48%, with the greater variation observed for broadleaf forests. The high levels of uncertainty in BNPP estimates suggest that both improvement and standardization of sampling procedures are required for more accurate estimates. Even then, high uncertainty in BNPP of terrestrial ecosystems is likely to remain.

To quantify the uncertainty associated with the root C inputs using the proposed approach, we estimated the total C inputs for grain–corn and soybean crops with average yields ($8 \text{ Mg grain ha}^{-1}$ for grain–corn and 5 Mg ha^{-1} for soybeans). We used the mean and standard deviation of S:R ratios for these crops (i.e., 5.6 ± 2.8 for grain–corn and 5.2 ± 3.1 for soybeans; Table 3) to calculate the relative plant C allocation coefficients. The HI was held constant (50% for corn, 40% for soybeans; Table 5) so that the amount of above-ground C inputs estimated using the mean, highest and lowest S:R ratio was the same (Fig. 3a and b). The above-ground C inputs for these two crops are

substantial; with the mean S:R ratio, the quantity of above-ground C inputs is greater than that from below-ground plant material. But the uncertainty associated with the S:R ratios shows that there is considerable variability related to estimates of below-ground C inputs. Taking this variability into account generated estimates as low as $142 \text{ g C m}^{-2} \text{ yr}^{-1}$ or as high as $424 \text{ g C m}^{-2} \text{ yr}^{-1}$ for corn ($\Delta = 282 \text{ g C m}^{-2} \text{ yr}^{-1}$), and as low as $112 \text{ g C m}^{-2} \text{ yr}^{-1}$ or as high as $442 \text{ g C m}^{-2} \text{ yr}^{-1}$ for soybeans ($\Delta = 330 \text{ g C m}^{-2} \text{ yr}^{-1}$). These large differences in C inputs show how crucial better estimates of BNPP are in predicting changes in soil organic C more accurately.

The variability associated with HI would also affect estimates of C inputs to the soil. To evaluate how variation in HI (and the associated variation in S:R ratio) would affect our estimates of C input, we varied the HI from 35 to 45% for calculating C inputs from soybeans (Fig. 3b). Using this range of HI values, typical of those measured for various crops (Hay, 1995), and holding the S:R ratio constant at 5.2, resulted in a low estimate of $275 \text{ g C m}^{-2} \text{ yr}^{-1}$ and a high estimate of $418 \text{ g C m}^{-2} \text{ yr}^{-1}$ for above-ground C inputs (i.e., $\Delta = 143 \text{ g C m}^{-2} \text{ yr}^{-1}$). The difference in C inputs

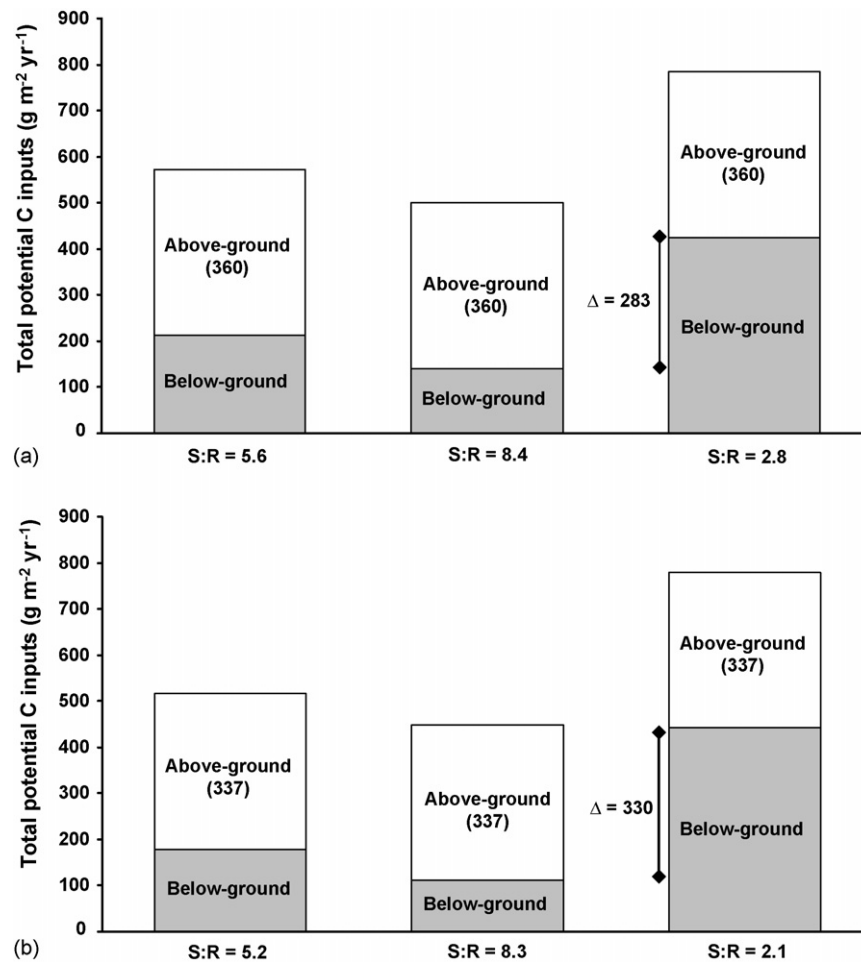


Fig. 3. (a) Uncertainty related to the annual C input from BNPP (C_R and C_E) component for an average yielding grain–corn crop ($8 \text{ Mg grain ha}^{-1}$). (b) Uncertainty related to the annual C input from BNPP (C_R and C_E) component for an average yielding soybean crop ($5 \text{ Mg grain ha}^{-1}$).

from variation in HI is much lower than that from variation in the S:R ratio (i.e., $330 \text{ g C m}^{-2} \text{ yr}^{-1}$; Fig. 3b). Prince et al. (2001) observed that variations in HI had a larger effect than variations in R:S ratios on NPP estimates in agricultural regions of the U.S. Midwest. In a sensitivity analysis they considered a 10% deviation for both the HI and S:R ratio (e.g., actual HI $\pm 0.1 \times$ actual HI), and concluded that only large deviations of $\pm 50\%$ in R:S ratios would have a significant affect on the estimates of NPP. Our data suggest that S:R ratios may, in fact, have such high variability, indicating that uncertainty related to BNPP is significant for agroecosystems.

5. Conclusions

The method proposed here for estimating NPP and annual C inputs to soil for Canadian agroecosystems is straightforward and easy to use. More importantly, however, the plant C allocation coefficients can be updated readily and estimates can be refined as new measurements emerge. The uncertainty associated with the below-ground C is substantial, and reflects our knowledge (or lack thereof, especially with regard to BNPP). Additional field measurements are therefore needed to reduce uncertainty for the estimates of root biomass and S:R ratios that are used to calculate BNPP. There are two advantages in assessing the range of uncertainty in C inputs. First, it can help account for variations in the predictions of C storage using simulation models. Secondly, the maximum C inputs for a particular cropping system define the upper boundaries for soil organic C sequestration rates; that is, you cannot sequester more C in soil than is added via photosynthesis.

Acknowledgement

The Model Farm Program for Canadian Agriculture project provided funding for this work. Thanks are extended to Drs. O. Andr n and T. K tterer for comments and discussion on an earlier draft of this paper.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.agee.2006.05.013](https://doi.org/10.1016/j.agee.2006.05.013).

References

- Allmaras, R.R., Nelson, W.W., Voorhees, W.B., 1975. Soybean and corn rooting in southwestern Minnesota. II. Root distributions and related water inflow. *Soil Sci. Soc. Am. Proc.* 39, 771–777.
- Amato, M., Pardo, A., 1994. Root length and biomass losses during sample preparation with different screen mesh sizes. *Plant Soil*. 161, 299–303.
- Anderson, E.L., 1988. Tillage and N fertilization effects on maize root growth and root:shoot ratio. *Plant Soil*. 108, 245–251.
- Balesdent, J., Balabane, M., 1996. Major contribution of roots to soil carbon storage inferred from maize cultivated soils. *Soil Biol. Biochem.* 28, 1261–1263.
- Barber, S.A., 1979. Corn residue management and soil organic matter. *Agron. J.* 71, 625–627.
- Barber, D.A., Martin, J.K., 1976. The release of organic substances by cereal roots into soils. *N. Phytol.* 76, 69–80.
- B hm, W., 1979. *Methods of Studying Root Systems*. Springer-Verlag, Berlin, 188 pp.
- Bolinder, M.A., VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., Janzen, H.H., 2006. Modelling soil organic carbon stock change for estimating whole-farm greenhouse gas emissions. *Can. J. Soil Sci.* 86, 419–429.
- Bolinder, M.A., 2004. Contribution aux connaissances de la dynamique du C dans les syst mes sol-plante de l'est du Canada [Contribution to the understanding of soil organic C dynamics for eastern Canadian agroecosystems]. PhD Thesis. Universit  Laval, Ste-Foy, Que., 125 pp.
- Bolinder, M.A., Angers, D.A., B langer, G., Michaud, R., Laverdi re, M.R., 2002. Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. *Can. J. Plant Sci.* 82, 731–737.
- Bolinder, M.A., Angers, D.A., Giroux, M., Laverdi re, M.R., 1999. Estimating C inputs retained as soil organic matter from corn (*Zea mays* L.). *Plant Soil*. 215, 85–91.
- Bolinder, M.A., Angers, D.A., Dubuc, J.P., 1997. Estimating shoot to root ratios and annual carbon inputs in soils for cereal crops. *Agric. Ecosyst. Environ.* 63, 61–66.
- Bowren, K.E., Cooke, D.A., Downey, R.K., 1969. Yield of dry matter and nitrogen from tops and roots of sweetclover, alfalfa and red clover at five stages of growth. *Can. J. Plant Sci.* 49, 61–68.
- Buyanovsky, G.A., Wagner, G.H., 1986. Post-harvest residue input to cropland. *Plant Soil*. 93, 57–65.
- Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., 1997. Root biomass allocation in the world's forests. *Oecologia* 111, 1–11.
- Campbell, C.A., de Jong, R., 2001. Root-to-stem ratios—influence of moisture and rate of N fertilizer. *Can. J. Soil Sci.* 81, 39–43.
- Campbell, C.A., Zentner, R.P., Liang, B.-C., Roloff, G., Gregorich, E.G., Blomert, B., 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan—effect of crop rotations and fertilizers. *Can. J. Soil Sci.* 80, 179–192.
- Campbell, C.A., Zentner, R.P., 1993. Soil organic matter as influenced by crop rotations and fertilization. *Soil Sci. Soc. Am. J.* 57, 1034–1040.
- Carter, M.R., Kunelius, H.T., Sanderson, J.B., Kimpinski, J., Platt, H.W., Bolinder, M.A., 2003. Productivity parameters and soil health under long-term 2-year potato rotations in Atlantic Canada. *Soil Tillage Res.* 72, 153–168.
- Donald, C.M., 1962. In search of yield. *J. Aust. Inst. Agric. Sci.* 28, 171–178.
- Eghball, B., Maranville, J.W., 1993. Root development and nitrogen flux of corn genotypes grown under combined drought and nitrogen stresses. *Agron. J.* 85, 147–152.
- Gill, R.A., Kelly, R.H., Parton, W.J., Day, K.A., Jackson, R.B., Morgan, J.A., Scurlock, J.M.O., Tieszen, L.L., Castle, J.V., Ojima, D.S., Zhang, X.S., 2002. Using simple environmental variables to estimate below-ground productivity in grasslands. *Global Ecol. Biogeogr.* 11, 79–86.
- Grogan, P., Matthews, R., 2002. A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. *Soil Use Manage.* 18, 175–183.
- Hansson, A.C., Andr n, O., 1986. Below-ground plant production in a perennial grass ley (*Festuca pratensis* Huds.) assessed with different methods. *J. Appl. Ecol.* 23, 657–666.
- Haugen-Kozyra, H., Juma, N.G., Nyborg, M., 1993. Nitrogen partitioning and cycling in barley–soil systems under conventional and zero tillage in central Alberta. *Can. J. Soil Sci.* 73, 183–196.
- Hay, R.K.M., 1995. Harvest index: a review of its use in plant breeding and crop physiology. *Ann. Appl. Biol.* 126, 197–216.

- House, G.J., Stinner, B.R., Crossley, D.A., Odum, E.P., 1984. Nitrogen cycling in conventional and no-tillage agro-ecosystems: analysis of pathways and processes. *J. Appl. Ecol.* 21, 991–1012.
- IPCC, 2000. In: Watson, R.W., Noble, I.A., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J. (Eds.), *Land Use, Land Use Change, and Forestry*. Cambridge University Press, Cambridge, UK.
- Izaurrealde, R.C., McGill, W.B., Robertson, J.A., Juma, N.G., Thurston, J.J., 2001. Carbon balance of the Breton classical plots over half a century. *Soil Sci. Soc. Am. J.* 65, 431–441.
- Izaurrealde, R.C., Juma, N.G., McGill, W.B., Chanasyk, D.S., Pawluk, S., Dudas, M.J., 1993. Performance of conventional and alternative cropping systems in cryoboreal subhumid central Alberta. *J. Agric. Sci. (Cambridge)* 120, 33–41.
- Izaurrealde, R.C., Nyborg, M., Chanasyk, D.S., Solberg, E.D., 1992. Effects of artificial erosion and amendments on soil and crop productivity. In: *Environmental Sustainability Initiative (PFRA-Agriculture Canada)*, University of Alberta, Edmonton, Alta., Canada.
- Kisselle, K.W., Garrett, C.J., Fu, S., Hendrix, P.F., Crossley, D.A., Coleman, D.C., Potter, R.L., 2001. Budgets for root-derived C and litter-derived C: comparison between conventional tillage and no tillage soils. *Soil Biol. Biochem.* 33, 1067–1075.
- Kunelius, H.T., Johnston, H.W., MacLeod, J.A., 1992. Effect of undersowing barley with Italian ryegrass or red clover on yield, crop composition and root biomass. *Agric. Ecosyst. Environ.* 38, 127–137.
- Kurz, W.A., Beukema, S.J., Apps, M.J., 1996. Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector. *Can. J. For. Res.* 26, 1973–1979.
- Kuzyakov, Y., Schneckenberger, K., 2004. Review of estimation of plant rhizodeposition and their contribution to soil organic matter formation. *Arch. Agron. Soil Sci.* 50, 115–132.
- Kuzyakov, Y., Domanski, G., 2000. Carbon input by plants into the soil. *Rev. J. Plant Nutr. Soil Sci.* 163, 421–431.
- Lal, R., 2004a. Soil carbon sequestration to mitigate climate change. *Geoderma* 123, 1–22.
- Lal, R., 2004b. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627.
- Laurenroth, W.K., 2000. Methods of estimating belowground net primary production. In: Sala, O.E., Jackson, R.B., Mooney, H.A., Howarth, R.W. (Eds.), *Methods in Ecosystem Ecology*. Springer, New York, pp. 58–71.
- Leyshon, A.J., 1991. Effect of rate of nitrogen fertilizer on the above- and below-ground biomass of irrigated bromegrass in southwest Saskatchewan. *Can. J. Plant Sci.* 71, 1057–1067.
- Li, Z., Kurz, W.A., Apps, M.J., Beukema, S.J., 2003. Belowground biomass dynamics in the carbon budget model of the Canadian forest sector: recent improvements and implications for the estimation of NPP and NEP. *Can. J. For. Res.* 33, 126–136.
- Lorenz, R.J., 1977. Changes in root weight and distribution in response to fertilization and harvest treatment of mixed prairie. In: Marshall, J.K. (Ed.), *The Below-ground Ecosystem: A Synthesis of 'Plant-associated Processes'*, Range Sci. Dept., Sci. Series No. 26. Colorado State University, Fort Collins, pp. 133–149.
- Marvel, J.N., Beyrouthy, C.A., Gbur, E.E., 1992. Response of soybean growth to root and canopy competition. *Crop Sci.* 32, 797–801.
- Mayaki, W.C., Teare, I.D., Stone, L.R., 1976. Top and root growth of irrigated and nonirrigated soybeans. *Crop Sci.* 16, 92–94.
- Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., et al. (Eds.), *Soil Organic Matter in Temperate Agroecosystems. Long-Term Experiments in North America*. CRC Press, Boca Raton, pp. 15–49.
- Pettersson, R., Hansson, A.C., Andrén, O., Steen, E., 1986. Above- and below-ground production and nitrogen uptake in Lucerne (*Medicago sativa*). *Swed. J. Agric. Res.* 16, 167–177.
- Piper, J.K., Kulakow, P.A., 1994. Seed yield and biomass allocation in *Sorghum bicolor* and F1 and backcross generations of *S. bicolor* × *S. halepense* hybrids. *Can. J. Bot.* 72, 468–474.
- Plénet, D., Lubet, E., Juste, C., 1993. Évolution à long terme du statut carboné du sol en monoculture non irriguée du maïs (*Zea mays* L.). *Agronomy* 13, 685–698.
- Prince, S.D., Haskett, J., Steininger, M., Strand, H., Wright, R., 2001. Net primary production of U.S. Midwest croplands from agricultural harvest yield data. *Ecol. Appl.* 11, 1194–1205.
- Rutherford, P.M., Juma, N.G., 1989. Shoot, root, soil and microbial nitrogen dynamics in two contrasting soils cropped to barley (*Hordeum vulgare* L.). *Biol. Fertil. Soils* 8, 134–143.
- Sauerbeck, D.R., Johnen, B.G., 1977. Root formation and decomposition during plant growth. *Soil Organic Matter Studies*, vol. 1. International Atomic Energy Agency, Vienna, pp. 141–148.
- Schapaugh Jr., W.T., Wilcox, J.R., 1980. Relationships between harvest indices and other plant characteristics in soybeans. *Crop Sci.* 20, 529–533.
- Scurlock, J.M.O., Olson, R.J., 2002. Terrestrial net primary productivity—a brief history and a new worldwide database. *Environ. Rev.* 10, 91–109.
- Sheaffer, C.C., Russelle, M.P., Heichel, G.H., Hall, M.H., Thicke, F.E., 1991. Nonharvested forage legumes: nitrogen and dry matter yields and effects on a subsequent corn crop. *J. Prod. Agric.* 4, 520–524.
- Smucker, A.J.M., McBurney, S.L., Srivastava, A.K., 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. *Agron. J.* 74, 500–503.
- Soon, Y.K., 1988. Root distribution of and water uptake by field-grown barley in a black Solod. *Can. J. Soil Sci.* 68, 425–432.
- Stanton, N.L., 1988. The underground in grasslands. *Ann. Rev. Ecol. Syst.* 19, 573–589.
- Tomm, G.O., Walley, F.L., van Kessel, C., Slinkard, A.E., 1995. Nitrogen cycling in an alfalfa and bromegrass sward via litterfall and harvest losses. *Agron. J.* 87, 1078–1085.
- Tran, T.S., Giroux, M., 1998. Fate of 15N-labelled fertilizer applied to corn grown on different soil types. *Can. J. Soil Sci.* 78, 597605.
- Troughton, A., 1957. The underground organs of herbage grasses. *Bulletin No. 44. Commonwealth Bureau of Pastures and Field Crops*, Hurley, UK.
- Van Noordwijk, M., Floris, J., De Jager, A., 1985. Sampling schemes for estimating root density distribution in cropped fields. *Neth. J. Agric. Sci.* 33, 241–262.
- Walley, F.L., Tomm, G.O., Matus, M., Slinkard, A.E., van Kessel, C., 1996. Allocation and cycling of nitrogen in an alfalfa-bromegrass sward. *Agron. J.* 88, 834–843.
- Warembourg, F.R., Paul, E.A., 1977. Seasonal transfers of assimilated ¹⁴C in grassland: plant production and turnover, translocation and respiration. In: Marshall, J.K. (Ed.), *The Below-ground Ecosystem: A Synthesis of 'Plant-Associated Processes'*, Range Sci. Dept., Sci. Series No. 26. Colorado State University, Fort Collins, pp. 133–149.
- Weaver, J.E., Zink, E., 1946. Annual increase of underground materials in three range grasses. *Ecology* 27, 115–127.
- Williams, M., Schwarz, P.A., Law, B.E., Irvine, J., Kurpius, M.R., 2005. An improved analysis of forest carbon dynamics using data assimilation. *Global Change Biol.* 11, 89–105.
- Xu, J.G., Juma, N.G., 1993. Above- and below-ground transformation of photosynthetically fixed carbon by two barley (*Hordeum vulgare* L.) cultivars in a typical cryoboroll. *Soil. Biol. Biochem.* 25, 1263–1272.
- Xu, J.G., Juma, N.G., 1992. Above- and below-ground net primary production of four barley (*Hordeum vulgare* L.) cultivars in Western Canada. *Can. J. Plant Sci.* 72, 1131–1140.
- Zan, C.S., Fyles, J.W., Girouard, P., Samson, R.A., 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. *Agric. Ecosyst. Environ.* 86, 135–144.