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SHORT COMMUNICATION

MAJOR CONTRIBUTION OF ROOTS TO SOIL CARBON STORAGE INFERRED FROM MAIZE CULTIVATED SOILS

JÉRÔME BALESDENT[1] and MAY BALABANE[2]*

[1]Laboratoire de Biogéochimie Isotopique, INRA-CNRS- UPMC, 4 place Jussieu, cc 120, F75252 Paris cedex 05, France and [2]Unité de Science du Sol, Institut National de la Recherche Agronomique, 78026 Versailles cedex, France

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The transfer of photosynthate below ground by roots may be a major input to the soil C pool, but is quantitatively the least understood, due to the technical difficulties associated with its measurement and labelling (Oades, 1995). Several researchers have traced root-derived C *in situ*, using $^{14}CO_2$ pulse labelling in the field (Warembourg and Paul, 1977), but have not evaluated the long-term contribution of root-C to soil C as compared to that of shoot-C. In order to trace plant-derived C *in situ*, we used the natural difference in $^{13}C/^{12}C$ between maize (*Zea mays* L.), a C4 plant, and existing soil organic C, derived from previous C3 vegetation. We found that the contribution of root-derived C to soil organic matter was 1.5 times that of stalks + leaves, whereas the corresponding ratio of biomasses was less than 0.5. We attributed this to a high below-ground production, and a relatively slow biodegradation of root-derived material.

We used a field experiment designed to trace soil organic matter (SOM) dynamics in croplands at the real agricultural scale (Balabane and Balesdent, 1992). The site was situated at La Minière (48°45′ N, 2°05′ E), France, at a Research Station of the National Institute of Agronomic Research (INRA). Maize was grown from 1987 to 1991, according to current maize grain production practices employed in Northern France. The monoculture was subjected to two treatments. In the first we returned the aboveground vegetative parts (leaves + stalks + sheaths) to the soil. In the second they were removed from the field. The experiment, sampling, and analytical procedures have been described by Balabane and Balesdent (1992) and Balesdent and Balabane (1992). The soil had only carried C3-type vegetation before the start of the experiment, thus the natural $\delta^{13}C$ of SOM traced the carbon derived from maize (Cerri *et al.*, 1985; Balesdent *et al.*, 1987).

$$\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard}] - 1;$$

the PDB standard was used.

The determination of maize-derived carbon (C_m) was based on the difference in $\delta^{13}C$ between maize and organic matter derived from the former C3 vegetation, using $C_m = C.\ (\delta - \delta_0)\ /\ \Delta$, where C is the carbon in the sample, δ its $\delta^{13}C$, δ_0 the $\delta^{13}C$ of the corresponding sample or fraction from the C3 reference soil. δ_0 was measured in the reference plot kept bare of any vegetation, and did not vary throughout the experiment. It equalled -26.3 and -27.6‰ for size-fractions 0–0.05 and 0.05–2 mm, respectively. Δ was the average difference in $\delta^{13}C$ between maize plant material and C3 material that has contributed to the initial SOM. $\Delta = +14.6$‰ was estimated as the difference between dead soil organic material coarser than 2 mm derived from maize ($\delta^{13}C = -12.8$‰) and from the reference plot ($\delta^{13}C = -27.4$‰). Despite a generally observed difference in $\delta^{13}C$ between roots and shoots (1‰), we used a common value of Δ for both treatments. The uncertainty on Δ could lead to a maximum relative error of 4% on the calculated value of C_m. The equation used is unbiased, even if decomposition leads to a shift in the isotope composition of the residual products (Benner *et al.*, 1987), provided that soil organic carbon dynamics is close to steady-state as in the case of our study.

The yearly mean and SD of total aboveground C production at harvest was 680 ± 75 g C m^{-2} (340 ± 45 in the grain and 340 ± 35 in the parts to be returned), with no significant difference between treatments. We sampled the topsoil (0–35 cm depth, 497 kg dry-soil m^{-2}, 4.0 kg C m^{-2}, 17% clay) two or more times each year. Maize-C accumulation was progressive (Fig. 1). We considered it as linear at the yearly time-step and calculated that the C accumulation in the treatment with no aboveground return was 61% of that observed in the treatment receiving returns (Fig. 1); the roots + collars having

*Author for correspondence.

incorporated 57 g C m^{-2} a^{-1}. The leaves and stalks have incorporated only 36 g C m^{-2} a^{-1}, assuming that the accumulation of below-ground material is the same in both treatments, an assumption which is supported by the generally accepted linearity of C decay in soils over this time-step and with these levels of inputs. This accumulation of root-derived C was surprisingly high when compared to the relative biomasses. Below-ground biomass was estimated to be less than 152 g C m^{-2}, at the 95% confidence level during the first growing season (Balesdent and Balabane, 1992). The corresponding total aboveground biomass was 730 g C m^{-2}, with the parts to be returned constituting 345 g C m^{-2}.

Two hypotheses could explain this large accumulation: high below-ground production and/or slow root decay. Assuming that above and below-ground production have similar decay kinetics, the measured accumulation rates would require a below-ground production of 537 g C m^{-2} a^{-1}, 1.56 times that of the stalks and leaves. Such a value is much higher than any known estimation of *in situ* below-ground production of C in maize or any other cereal

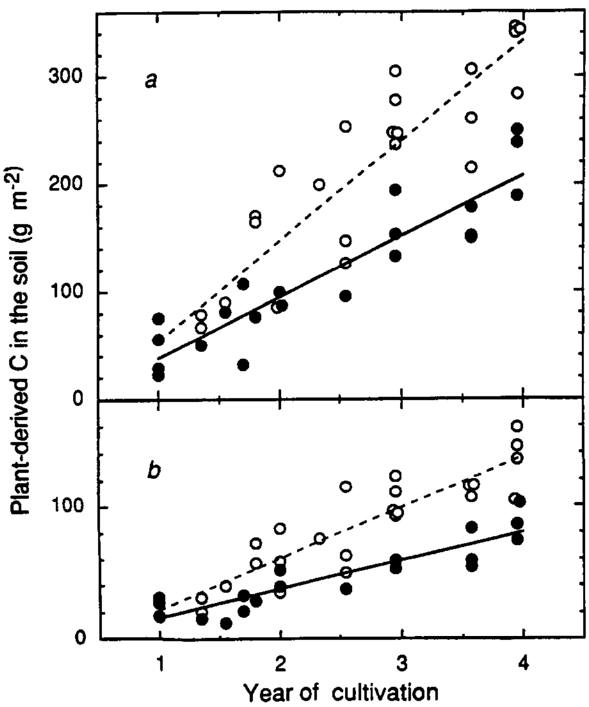

Fig. 1. Accumulation of maize-derived organic carbon in soil (0–35 cm), as estimated from ^{13}C natural abundances during 4 years of cultivation with two treatments: total vegetative parts returned to the soil (open circles), and only the below-ground parts returned (solid circles). (a) Total organic carbon (0–2 mm) in the soil. (b) Particulate organic carbon (light material sized 0.05–2 mm). Date 1 is the day preceeding the first harvest, and is common to both treatments. The rates of accumulation of organic C in the total soil and their 95% confidence intervals were 93 ± 16 g m^{-2} a^{-1} (dotted line) and 57 ± 12 g m^{-2} a^{-1} (plain line) in the two treatments, respectively. For particulate organic C, they were 38 ± 6 and 21 ± 5 g m^{-2} a^{-1}.

(Merckx *et al.*, 1985; Davenport and Thomas, 1988). Furthermore, most of this high below-ground productivity would consist of ephemeral products such as root exudates, leading to colloidal and microbial C. Such products would be found in the fine (0–0.05 mm) fraction and not in the particulate organic matter fraction (0.05–2 mm), which contains products derived from the structural parts of the plants, mainly hemicellulose, cellulose and lignin. On the contrary, our results revealed that root-derived C contributed to both fractions in the same proportion as stalks and leaves (Fig. 1b). From this observation we deduced that the large accumulation was partially due to a slower decay of root-derived C compared to aboveground C. The slower decay rate of root-C compared to aboveground-C has been pointed out in incubation experiments under controlled conditions (Broadbent and Nakashima, 1974; Mary, 1987). Two processes are known to lower the decay rate and to increase the stabilisation-to-mineralisation ratio of C in soils: on one hand the higher lignin to nitrogen ratio in root material compared to leaves and stalks (i.e. 32 and 11 in the present study, respectively); and on the other hand, the direct introduction of root-derived products into the soil clay matrix, which tends to physically protect them from microbial degradation (Oades, 1995).

Roots have long been suspected to be an important source of SOM. This has mainly been inferred from carbon balance studies, where the aboveground inputs could only explain one part of the soil carbon stocks and their variations (Campbell *et al.*, 1991; Fisher *et al.*, 1994). Here we have assessed this source from direct measurement of root-derived C accumulation, considering only the upper part of the soil, under maize cultivation. Since maize is known to have a below-ground production lower than perennial cereals and grasses (Merckx *et al.*, 1985; Davenport and Thomas, 1988), our results suggest that there would be a clear predominance of root-derived C in the stored soil C of croplands and grasslands. Soil organic carbon has often been suggested as a potential sink of atmospheric CO_2 (Houghton, 1995). According to our result, rhizodeposition may be the major flux concerned. The response of the soil C pool to an increased atmospheric CO_2 would be more dependent on changes of carbon allocation pattern in the vegetation (Norby *et al.*, 1992) than on changes of productivity.

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