Carbon sequestration capacity in a semiarid ecosystem: A carbon balance approach

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ABSTRACT

Here, we used two C balance approaches to estimate total belowground C allocation (TBCA) in three representative land uses in a Mediterranean ecosystem (late-successional forest, abandoned agricultural field, rainfed olive grove). Our objectives were: 1) to asses the response of TBCA and its components to changes in land use; 2) to evaluate how soil water erosion and changes in C stored in roots, soil and litter layer altered our estimates of TBCA; 3) to determine annual net ecosystem productivity, and examine C allocation patterns at each land use.

Key words: Belowground carbon allocation; land use change; Mediterranean ecosystem

INTRODUCTION

Alterations in the size of the soil C pool at a specific location are determined by the relative changes in the inputs (aboveground and belowground net primary production) and outputs (erosion and decomposition of plant material and soil organic matter) of C over yearly and longer time scales. Vegetation allocates carbon (C) belowground to produce coarse and fine roots, for root respiration and exudates, and to support mycorrhizae. Raich and Nadelhoffer (1989) proposed a conservation of mass approach to estimate total belowground C allocation (TBCA) (g C m^{-2} yr^{-1}) in ecosystems where the stocks of soil organic matter, roots, and litter were assumed to be near steady sate:

$$TBCA=F_S -F_A \qquad \text{Eq.1}$$

Where F_S is surface CO_2 efflux, and F_A is aboveground litterfall. As the near-steady-state assumption is sometimes problematic, Giardina and Ryan (2002) proposed a similar approach that dictates that C outputs from the soil must equal C inputs minus any change in C storage:

$$F_S+F_E=TBCA+F_A-\Delta[C_S+C_R+ C_L]/\Delta t \qquad \text{Eq. 2}$$

Where surface CO_2 efflux (F_S) and export of C via erosion (F_E) are the C outputs, and aboveground litterfall (F_A) and C allocated belowground by plants (TBCA) are the C inputs. Important storage component of C in soils include coarse roots (C_R), the litter layer (C_L), and mineral soil organic matter (C_S). Solving for TBCA yields:

$$TBCA=F_S+F_E-F_A + \Delta[C_S + C_R + C_L]/\Delta t \qquad \text{Eq. 3}$$

Here, we used both C balance approaches to estimate TBCA in three representative land uses in a Mediterranean ecosystem (late-successional forest, abandoned agricultural field, rainfed olive grove). The specific objectives were: 1) to determine the response of TBCA and its components to changes in land use; 2) to evaluate how changes in C stored in roots, soil and litter layer alter our TBCA estimates; 3) to determine annual net ecosystem productivity, and examine C allocation patterns at each land use.

MATERIALS AND METHODS

Study area

The study area was located in Cehegin in the northwest of the province of Murcia in S.E. Spain. Three land uses were selected to carry out the study: 1) a forest area, 2) an abandoned agricultural field which was cultivated with cereal until about 25 years ago, and 3) a rainfed olive grove without terraces and regularly ploughed following the contours, which has been cultivated for 100 years. The forest and abandoned field are covered by a typical Mediterranean shrubland (*R. officinalis, Q. coccifera,* and *J. oxycedrus*) with scattered Aleppo pines (*P. halepensis*). The soils in the study area, with a loam texture, derived from limestone colluvia (forest and olive) and Triasic marl colluvia (abandoned field), are classified as Petric calcisol, Hypercalcid calcisol and Calcaric regosol, respectively, according to FAO soil taxonomy.

Measurements and calculations

Carbon stocks

At each land use, 24 sampling points at 10 cm depth were distributed in a stratified random manner. A composite sample from each point included a non-disturbed sample (core of 100 cm^3 volume) for bulk density measurements, and a disturbed sample for organic C (SOC) and total nitrogen (TN) analysis. Soil organic carbon stock (g m^{-2}) was computed as a product of the OC concentration, bulk density and depth for each sampling point.

Above-ground biomass (AGB) was estimated from plot-based measurements of shrub and tree stem basal diameters in order to estimate AGB from species-specific allometric relationships. The C content of AGB was estimated to be 48 % of dry weight.

Below-ground biomass (BGB) was estimated using the core method. Soil cores (N=24) (8 cm in diameter and 10 cm depth) were collected at each land use. Roots were weighted, ground, and analyzed for C and N content. We calculated BGB-C values (g C m^{-2}) by multiplying the % C values by the total root sample weight and core size.

Components of the belowground C budget

F_S was measured in situ with a portable soil respiration gauge fitted with a soil respiration chamber (LI-6400- 09, LI-COR, NB, USA). At each land use, we installed 30 PVC circular collars (5 cm depth, 10 cm diameter). Measurements of F_S were always performed between 9:00 and 12:00 (solar time) at monthly intervals over two years.

To measure the rates of soil water erosion and quantify the organic C losses in sediments and runoff two closed erosion plots (8m large×2m width) were installed in the forest and olive grove. In the abandoned field, three sediment traps (Gerlach type) were set up in different locations at the bottom of the slope.

F_A was collected monthly in ten trays (0.25 m^2 each) at each land use, dried at 60º C, weighted, and analysed for C and N content. We estimated above-ground C-litter production (in g C m^{-2} y^{-1}) by multiplying the sample weight by the averaged % C values.

The annual change in C in mineral soil in the olive grove and abandoned agricultural field was estimated using a space-for-time approach. In the late-successional forest, we assumed that annual changes in C_S were negligible due to near-steady-state condition in this land use. The annual increases in coarse and fine roots estimates were obtained using the root in-growth core technique. The annual accumulation rates in litter layer C mass were estimated as the difference between the annual aboveground litterfall input and our aboveground litter decomposition C loss estimates at each land use. To measure above-ground litter decomposition rates (k_c) we used the *litterbag* method.

Net Primary Production

Annual above-ground net primary productivity (ANPP) was determined over a two-year period (2006-2008) using a variety of pruning, harvesting, litterfall collection, and allometric methods appropriate for each land use. TBCA numbers were converted to production estimates (below-ground NPP) by assuming that 50 % of the C efflux was root and mycorrhizal respiration (the other 50 % incorporated new tissue) (Ryan, 1991). We summed above-ground and below-ground net primary production values to estimate net primary production (NPP-C) in each of the land uses.

RESULTS AND DISCUSSION

Carbon pools in each land use

Pools (g m^{-2}) of soil organic C were higher in forest than abandoned field or olive grove (Table 1). The whole ecosystem carbon pool was more than two times higher in forest than in the abandoned field or olive grove, with approximately 53, 88 and 66.6 % of the C stored belowground for forest, abandoned field and olive grove, respectively.

Table 1. Carbon Pools (mean ± standard error) (g C m^{-2}) for each land use.

	Forest	Abandoned field	Olive grove
Aboveground biomass C	3293.8 ± 2072,6	351.3 ± 49,64	830.3 ± 52.1
Belowground biomass C	313.4 ± 63.9	168.8 ± 34,4	74.2 ± 23.5
SOC	3399.5 ± 239.7	2337.8 ± 566.5	1506.8 ± 396.8
Total Ecosystem C Pool	7000.5	2856.8	2410.6

Components of the TBCA budget

Soil surface CO_2 efflux at our site (F_S) was the largest component on the TBCA approach across land uses (forest>abandoned field>olive grove) (Table 2). Carbon losses by soil water erosion (F_E) were higher in the olive grove than in the abandoned field and forest, although were negligible compared to F_S (less than 1% across land uses) and had little effect on estimates of TBCA. Including estimates of C losses by erosion in the calculation of TBCA yielded estimates of TBCA that were 0.19 (in forest) and 0.37 (in both abandoned field and olive grove) % higher than estimates calculated assuming $F_E = 0$.

Table 2. Annual carbon fluxes (g C m^{-2}) and TBCA within each land use.

	Forest	Abandoned field	Olive grove
Annual C from soil-surface respiration (F_S)	766	648	427
Annual litterfall C (F_A)	128.4	88.4	15.6
Annual C loss by soil and water erosion (F_E)	1.43	2.21	2.58
Annual change in soil C (ΔC_S)		18.74	-16.74
Annual change in litter layer C (ΔC_L)	76.4	56.6	14.3
Annual change in coarse root C (ΔC_R)	45	88.8	33.8
TBCA calculated as $F_S - F_A$	649.84	559.42	372.6
TBCA including C exported from the site (F_E)	650.8	560.8	374.9
TBCA ($F_S - F_A + F_E + \Delta C_S + \Delta C_L + \Delta C_R$)	760.1	674.2	374.9
TBCA ($F_S - F_A + F_E + \Delta C_S$)	650.3	579.6	356
TBCA ($F_S - F_A + F_E + \Delta C_L$)	726.7	617.4	383.5
TBCA ($F_S - F_A + F_E + \Delta C_R$)	683.7	598.9	385.2
ANPP	260.4	174.9	93.7

We quantified the effect of changes in C storage in soil, litter layer, and roots on TBCA by comparing TBCA estimated with the full model in Eq. (3) with the TBCA estimated assuming zero change in C storage (Eq.1). Assuming that $\Delta[C_S + C_R + C_L]/\Delta t = 0$ yielded estimates of TBCA that were 20% lower than estimates calculated from the full model (Eq.3). The abandoned field had the largest bias (- 26%), followed by forest (- 17.5%) and olive grove (- 16.6%). Annual increases in litter layer C mass were responsible for most of the increase in C storage in forest. Including estimates of litter layer C mass in the calculation of TBCA reduced the bias in TBCA to an average of a 5.8 % underestimate in forest. However, in the abandoned field and olive grove, annual increases in roots were responsible for most of the increase in C storage, reducing the bias in TBCA to an average of a 12.3 and 6.3% underestimate in abandoned field and olive grove, respectively.

ANNP, TBCA AND ALLOCATION PATTERNS

Our annual above- and belowground production estimates of forest and abandoned field were higher than that of olive grove (Table 2). Annual net ecosystem productivity was estimated to be 640, 512 and 281 g C m^{-2} y^{-1} for forest, abandoned field and olive grove, respectively. These values are in agreement with those reported by Valentini et al. (2000) for the cross-site EUROFLUX study (from a net source of 100 to sink of 660 g C m^{-2} yr^{-1}).

CONCLUSIONS

The late-successional forest at our site has the potential to sequester more C per m^2 than the abandoned field and olive grove. Greater total belowground C allocation and aboveground litter inputs, together with slower litter decomposition rates observed in forest with respect to abandoned field and olive grove explain the higher amounts of organic C stored in the surface horizon of the forest soil.

Despite annual inputs of 889 (forest), 762 (abandoned field) and 390 (olive grove) g C m^2 y^{-1} as F_A and TBCA, changes in C stored in litter, soil and roots were 15.25 and 7 % of TBCA for forest, abandoned field and olive grove, respectively, indicating that much of TBCA was quickly returned to the atmosphere as F_S, especially in the olive grove. As the size of the annual input of organic materials and decomposition rates are key factors regulating SOM pool sizes, conservation measures such as no till, cover crops, or return the pruning residues to the soil may help alleviate this problem in the olive grove.

Losses of C by erosion at this scale of measurement, while important on century to millennial timescales, are too small to be major contributors to inter-annual C balance in net ecosystem production.

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