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Comparing carbon fluxes between different stages of secondary succession of a karst grassland

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ABSTRACT

Abandonment of marginal agricultural areas with subsequent secondary succession is a widespread type of land use change in Mediterranean and mountain areas of Europe, leading to important environmental consequences such as change in the water balance, carbon cycling, and regional climate. Paired eddy flux measurement design with grassland site and tree/shrub encroached site has been set-up in the Slovenian Karst (submediterranean climate region) to investigate the effects of secondary succession on ecosystem carbon cycling. The invasion of woody plant species was found to significantly change carbon balance shifting annual NEE from source to an evident sink. According to one year of data succession site stored $-126 \pm 14\,g\,C\,m^{-2}\,y^{-1}$ while grassland site emitted $353 \pm 72\,g\,C\,m^{-2}\,y^{-1}$. In addition, the seasonal course of CO_2 exchange differed between both succession stages, which can be related to differences in phenology, i.e. activity of prevailing plant species, and modified environmental conditions within forest fragments of the invaded site. Negligible effect of instrument heating was observed which proves the Burba correction in our ecosystems unnecessary. Unexpectedly high CO_2 emissions and large disagreement with soil respiration especially on the grassland site in late autumn indicate additional sources of carbon which cannot be biologically processes, such as degassing of soil pores and caves after rain events.

1. Introduction

Grasslands contribute to the biosphere–atmosphere exchange of greenhouse gases (GHGs) mainly with fluxes of carbon dioxide (CO_2) and methane (CH_4) that are intimately linked to management (Soussana et al., 2007). Cutting regime, grazing, fertilization and other disturbances can severely alter different components of carbon cycle and can strongly influence rates of carbon gain or loss. Contrary, effects on carbon cycling are also expected when human disturbances seize and succession towards potential vegetation (e.g. shrubland or forest) starts. In relation to land use, the spontaneous transition of grasslands to forests, which is especially widespread in regions where the agriculture is limited due to unfavorable geomorphological, soil and climatic conditions, has been one of the most evident environmental changes in recent decades in Europe and beyond (McLauchlan et al., 2006; Mottet et al., 2006; MacDonald et al., 2000). At global level it has been estimated that this abandoned area amounts 385–472 × 10^6 ha (Campbell et al., 2008). Hurtt et al. (2006), using HYDE (Historical Database of the Global Environment, by Klein, 2001), estimated that 269 × 10^6 ha of crop lands were permanently converted to other land uses between the years 1700 and 2000. It has been estimated that about 13% of agricultural areas were abandoned in Europe in four decades since 1961 (Rounsevell et al., 2003, 2006) with the Mediterranean (Pinto-Correia, 1993) and mountain regions (MacDonald et al., 2000) being subjected to the most intensive marginalizaton and abandonment. For Italy, Falcucci et al. (2007) report on forest share increase from 18.7% of national territory in 1960 to 32.5% in 2000; the share of agricultural (especially pasture) areas dipped simultaneously from 56.6% down to 38.5%. Similar pattern was also observed for SW part of Slovenia (Kaligarič et al., 2006).

When grasslands are abandoned, becoming overgrown by woody plants, their carbon balance drastically changes. This issue has been addressed in several studies (Post and Kwon, 2000; Jackson et al., 2002; McKinley and Blair, 2008) but, despite of

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the rapid growth of regional and global networks for the measurement of biosphere and atmosphere gas exchanges (Valentini et al., 2000; Baldocchi, 2003; Papale et al., 2006), including the Mediterranean region (Miglietta and Peressotti, 1999; Reichstein et al., 2002; Rambal et al., 2003, 2004; Xu and Baldocchi, 2004; Ciais et al., 2005; Ma et al., 2007; Pereira et al., 2007; Serrano-Ortiz et al., 2007), the consequences of regional land use changes on the carbon cycle remains poorly understood. Thus, it is urgent to understand the change in carbon balance of the abandoned and afforested agricultural lands of Europe and specifically of the Mediterranean basin. Shifting dominance among herbaceous and woody vegetation alters net primary production (NPP), plant allocation, rooting depth and soil processes affecting nutrient cycling and carbon storage. The invasion of woody vegetation into grasslands is generally thought to lead to an increase in amount of carbon in those ecosystems, changing two major carbon pools, woody plant biomass and soil organic matter (e.g. Alberti et al., 2008). While increasing aboveground biomass represents a dominant sink of carbon, soil carbon pools show an inconsistent response under woody plants encroachment. In fact, this response has been found to be extremely dynamic and dependent on vegetation, litter recalcitrance properties and on environmental conditions that influence decomposition. Jackson et al. (2002), studying carbon budgets of woody plants invading grasslands with different precipitation regimes, found a clear negative relationship between precipitation and changes in soil organic carbon and nitrogen, with drier sites gaining and wetter sites losing carbon. In some cases the rate of the loss overrode the sink strength gained by aboveground biomass increment. Water relations also proved to be of significant importance for carbon budget of invaded grasslands in other studies (Scott et al., 2006; Kurc and Small, 2007). Generally, much of the variation in grassland net ecosystem exchange (NEE) is constrained by the amount of precipitation (Flanagan et al., 2002). In this respect, arid and semi-arid grasslands are especially sensitive to inter-annual variability in precipitation (Huxman et al., 2004). For example, Nagy et al. (2007) studying NEE dynamics and carbon balance of a dry, extensively managed sandy grassland on the Great Hungarian Plain in the years 2003 and 2004 found that it a weak source of carbon in 2003 (80 g C m^{-2}), owing to the exceptionally hot and dry conditions, while it was a moderate sink in 2004 (−188 g C m^{-2}), when the amount of precipitation was considerably above the 10-year average. Carbon dioxide exchange of dry annual C_3 grassland and a proximate oak-grass savanna was also studied by Ma et al. (2007). This 5–6-year study focused on inter-annual variation in NEE, which was found to be significantly related to length of growing season for the savanna, grassland, and tree canopy: annual net carbon exchange (NEE) ranged from −155 to −56 g C m^{-2} y^{-1} and from −88 to 141 g C m^{-2} y^{-1} at the savanna and nearby grassland, respectively. Gross primary productivity (GPP) and ecosystem respiration (R_{eco}) depended primarily on amount of seasonal precipitation. Inglima et al. (2009) reported that R_{eco} is stimulated after first autumn rains following summer drought thus resulting in positive NEE in different Mediterranean ecosystems.

A large portion of arid ecosystems in Mediterranean countries is characterized by carbonate rocks, the bedrock material in Karst systems. Carbonate rocks outcrop on ca. 12% of the water-free Earth surface (Ford and Williams, 1989) and may play a direct role in the global carbon cycle. Dissolution of limestone or dolomite, weathering and carbonate precipitation are the key reactions of geological cycling of CO_2 and are mostly governed by the physical–chemical conditions of the soil environment. Several studies suggest that cycling through the inorganic pool is an important contribution to the ecosystem CO_2 fluxes in Mediterranean ecosystems and should not be neglected when partitioning the fluxes (Emmerich, 2003; Kowalski et al., 2008; Inglima et al., 2009; Serrano-Ortiz et al., 2009, 2010).

Thus, the research of carbon cycling in karst grasslands that are exposed to invasion of woody plants is challenging in many respects. There are, however, difficulties that are inherent to experimentation in these karst ecosystems. To start with, relief with depressions and sinkholes might affect, together with wind conditions, the quality of eddy flux measurements. This necessitates a careful selection of the measuring site, for which, however, the history of use has to be well-known, especially when C cycling is studied in relation to natural succession. Secondly, the high degree of heterogeneity of the ecosystems has to be taken into account. This heterogeneity is to a large extent related to spatial heterogeneity of soil, which can be for example extremely shallow but can also develop deeper organic patches. Stony soil with rocks limits the application of some conventional methods (e.g. root exclusion for partitioning of soil CO_2 efflux) and makes other methods difficult to be applied.

In the present study a paired eddy flux measurement design was used in order to assess the NEE of two ecosystems: an extensively used semi-dry pasture and proximate abandoned grassland with woody plants encroachment (succession site henceforth) at Podgorski Kras plateau (SW Slovenia). The use of two eddy towers allowed detection of the influence of land use change, in our case secondary succession, on C fluxes without confounding influences relating to meteorological variability, a serious shortcoming of measurements with single eddy flux towers (Don et al., 2009). Until now the altered pattern and magnitude of NEE has only rarely been investigated by paired eddy-flux measurements (e.g. Scott et al., 2006). The objectives of this paper are: (I) to analyze the yearly NEE courses and seasonal changes in NEE for the grassland and the succession site, (II) to compare the sites in their NEE response to weather conditions, precipitation patterns and phenological development, and (III) to assess the role of the Burba correction for accurate measurements of the carbon balance.

2. Materials and methods

2.1. Study area

The study was conducted at the Podgorski Kras plateau (45°33′N, 13°55′E, 400–430 m.a.s.l.) in the sub-mediterranean region of Slovenia (SW Slovenia; Table 1). Due to its position at the transition between the Mediterranean and central Europe, the karst landscape of this area has been subjected to major human influences since at least 3000 years BC. Overgrazing effects during the past centuries almost completely destroyed vegetation cover and caused severe soil erosion which resulted in a stony, bare landscape. Later, economic development leads to abandonment of agriculture which caused a slow but extensive spontaneous afforestation. During the 18th century, some Austrian pine (*Pinus nigra* L.) plantations were also established. Historic human activities and natural conditions resulted in today's diverse landscape with co-occurring successional stages ranging from grasslands to the secondary oak forests.

Woody plant encroachment is characterized by shrubs of early succession stages (*Juniperus communis*, *Prunus mahaleb*, *Cornus mas*, *Cotinus coggygria*) and also tree species of mid- and late succession (*Quercus pubescens*, *Ostrya carpinifolia*, *Fraxinus ornus*). Species-rich semi-dry calcareous grasslands of the *Scorzoneretalia* order still cover around 20% of the area, but more than 60% of former grasslands were transformed to forest and shrub vegetation types (Kaligarič et al., 2006). The most abundant grassland species are *Bromopsis erecta*, *Carex humilis*, *Stipa eriocaulis*, *Centaurea rupestris*, *Potentilla tommasiniana*, *Anthyllis vulneraria*, *Galium corrudifolium* and *Teucrium montanum*.