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Surface albedo raise in the South American Chaco: Combined effects of deforestation and agricultural changes

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ABSTRACT

Deforestation affects climate and the energy balance of the Earth not only through the release of greenhouse gases but also through shifts in the physical properties of the surface. These physical effects can be strongly dependent not only on the deforestation event but on the land use choices and management that follow it. Here we explored how the albedo and radiation balance of the dry subtropical Chaco forests of South America changed over the last decade in response to both deforestation and land use/management. For the whole region we analyzed changes in the mean annual albedo derived from MODIS imagery and their relation with the dominant land use trajectories for a 12-year period (2000–2012). In two focal areas we identified how specific land uses and management shifts affected the seasonality of surface albedo and green vegetation cover, quantifying their associated radiation budget changes and radiative forcing effects. Deforestation accounted for 83% of the regional albedo increase observed in Chaco, yet, land use and land management changes were also a main driver of albedo shifts, explaining the rest of the albedo rise occurred in the region. Albedo raises increased the mean annual outgoing shortwave energy flux at the top of the atmosphere producing a biophysical cooling effect which was strongly dependent on the land use choice and agricultural management, ranging from $-8\,W\,m^{-2}$ in silvopastoral systems to $-17\,W\,m^{-2}$ under single annual cropping schemes. These values are equivalent to a reduction in atmospheric CO_2 of 12–27 Mg C ha^{-1}, or 15–55% of the typical emissions that accompany deforestation in this region. Land use and management choices in the Chaco region produce strong divergences in the resulting albedo seasonality that should not be ignored in the assessment of their net climatic effects and the discussion of possible mitigation actions.

1. Introduction

The effects of deforestation on climate are now widely recognized (Bright et al., 2015; Zhao and Jackson, 2013). It has been shown that deforestation may affect the climate through changes in biogeochemical processes (e.g. carbon cycling) which involve global and large time scales, and through changes in surface biophysical properties (i.e. albedo, latent/sensible heat partition, canopy conductance and surface roughness among others) which usually manifest with fast reactions, at global, regional and/or local scales and may counteract or enhance biogeochemical processes (Baldocchi and Ma, 2013; Bonan, 2008; Dixon et al., 1994; Rotenberg and Yakir, 2010). However, a key aspect that has been poorly explored so far is related to how the different purposes of deforested areas and the agricultural practices applied to them may modulate these climatic effects (Boisier et al., 2013; Bright et al., 2015; Jeong et al., 2014; Luyssaert et al., 2014). How does the climatic forcing change if deforested areas are devoted to grain or forage production? Does single vs. double cropping (i.e. one or two crops per year) have similar climatic effects? These are important questions that need to be answered in order to better understand the effect of human decisions on climate.

Similar to the carbon release after deforestation, which produce a biogeochemical perturbation in radiation balance of the earth (Myhre et al., 1998), the change in surface albedo that usually accompanies deforestation is a key climatic aspect that may over-

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come the global effects over the carbon cycle (Beltrán-Przekurat et al., 2011; Betts, 2000; Bonan, 2008; Zhao and Jackson, 2013). Forests usually present lower albedo than agriculture lands (Loarie et al., 2010) and as a consequence, deforestation reduces the amount of shortwave (SW) solar radiation captured by the ecosystem, resulting in a albedo biophysical cooling (Betts, 2000; Bright et al., 2014, 2015). Deforestation may also affect the energy budget and global climate through more complex atmospheric effects (Davin and Noblet-Ducoudré, 2010). For instance, this land-cover change may alter the radiation budget in longwave component, since forest have significantly higher heat transfer capacity than agriculture systems (Jackson et al., 2008), but this effect would be mostly absorbed by the lower atmosphere without generating net changes in the global radiation budget (Lee, 2010). In addition, this land-cover change may modify planetary albedo in different directions if the lower evapotranspiration of agriculture systems (Nosetto et al., 2012) translates into decreased cloud formation (Werth and Avissar, 2002), something that can be particularly relevant in the humid tropics (Davin et al., 2007). Deforestation may also affect energy balance and impact on local climate through changes in evapotranspiration rates (Lee, 2010), but its comparison with global effects are more difficult to quantify (Davin et al., 2007). In addition, in arid/sub-humid areas with high radiation load, the changes in the radiation balance that follows vegetation changes are likely more important than evapotranspiration contrasts between different vegetation covers because they tend to evapotranspire most of rainfall inputs (Rotenberg and Yakir, 2010; Santoni et al., 2010).

In order to compare both global effects (albedo and carbon) the metric "radiative forcing" is widely used, referring to the change in net irradiance at the tropopause level and giving a measure of the global warming/cooling potential of any anthropogenic or natural forcing (Davin et al., 2007; Forster et al., 2007; Ward and Mahowald, 2015). Several studies have shown that when albedo and carbon effects are considered the net outcome becomes highly dependent on the climatic context. While in boreal and tropical regions net cooling and net warming are respectively the expected results (Betts, 2000), in temperate regions the net outcome is more uncertain and highly dependent on local conditions (e.g. crop choice, management practices, etc.) (Bala et al., 2007; Jackson et al., 2008; Salazar et al., 2015). Particularly, the expansion of agriculture into subtropical dry forests is of key relevance because of its current magnitude and relatively high biophysical vs. biogeochemical effects associated to the high radiation levels and smaller total carbon pools of these regions (Anderson et al., 2011; Jackson et al., 2008). Recent studies evidenced the strong biophysical effects of the replacement of temperate dry forests by annual crops in central Argentina (Houspanossian et al., 2013).

The albedo biophysical climatic forcing associated to the different purposes of deforested areas (i.e. land uses) and its different management practices have been poorly considered, despite of the strong contrasts they may present. Globally, deforested areas are mainly devoted to two land uses: forage production (with perennial pastures) or grain production (with annual crops) (Foley et al., 2005). These land uses present canopies with different biophysical properties given by contrasting morphological, architectural, phenological, and chemical properties (Ahmad and Lockwood, 1979), that may result in different radiative forcings (Davin et al., 2007). For example, grain production systems usually include a fallow period each year with no vegetation cover, which creates noticeable contrasts of albedo and roughness with active vegetation covers (e.g. perennial pastures) (Nosetto et al., 2012). In addition, the changes that occur within the same land use and that do not result in a land use change are also able to modify the radiative forcing with a similar magnitude than land cover change (Luyssaert et al., 2014). Besides irrigation, whose climatic effects have been the main focus of attention (Lobell et al., 2006), the effects of other land management changes aspects such as sowing dates and phenology, tillage system, or crop species choice, have been hardly considered (Davin et al., 2014; Jeong et al., 2014; Luyssaert et al., 2014; Zhang et al., 2013). Recent studies have shown that management changes may strongly impact local, regional and global climate through shifts in surface albedo and other surface properties (Davin et al., 2014; Jeong et al., 2014; Luyssaert et al., 2014). Although land cover changes explained most of land transformations in the last century (Ramankutty et al., 2008), it is expected that land management changes will become highly relevant in the near future as increasing food demand and technological changes operate under limited land availability (Ramankutty et al., 2002) and a higher climate variability (Sadras et al., 2003).

In southern South America, a continuous advance of the agricultural frontier into the dry subtropical forests (semiarid Chaco) has been taking place in the last decades (Vallejos et al., 2015), being the cleared areas mostly devoted to pastures, for cattle ranching, and grain annual crops (Houspanossian et al., 2016). Given the large areal extension of the Chaco and the large diversity of land users (Baldi et al., 2015), different management strategies are also commonly observed within each land use option. For instance, in ranching systems, open pastures, based on perennial species coexist with silvopastoral schemes based on native tree species or planted exotic ones (Glatzle, 2004; Glatzle and Stosiek, 2002). On the other hand, in the last decade many agricultural farmers have changed their management strategies replacing double crop systems (i.e. a winter/spring crop followed by a summer crop) by late summer single crops, in order to improve soil moisture conditions and reduce farming risks (Giménez et al., 2015). Understanding how the different land trajectories observed in the last decade modify the radiation budget becomes particularly relevant in a region like the Chaco that has a high solar radiation load and shows fast environmental changes.

The goal of this work was to analyze the effects of the different land trajectories observed in the Chaco dry forests on the surface albedo and the radiation budget. For this purpose, we performed two analyses at different spatial scales (regional and local). At the regional scale, we analyzed the spatial and temporal variability of the surface albedo for the whole Chaco region and its relation with land trajectories. At the local scale, we focused in how the different land uses and management practices affect the seasonality of surface albedo and green vegetation cover and, through remote sensing and radiative modeling, we quantified the radiation budget changes and the radiative forcing associated to these transformations. We performed this local analysis in two focal areas of the Chaco region (Santiago del Estero, Argentina and Filadelfia, Paraguay).

2. Materials and methods

2.1. Study region

The semiarid Chaco region is a vast sedimentary plain of 61.3 M hectares in size that extends through the north-central part of Argentina, east of Bolivia and the western part of Paraguay (Olson et al., 2001) (Fig. 1). This region is one of the flattest semiarid sedimentary areas of the planet, with a very large fraction of the land with slopes <0.1% (Jobbágy et al., 2008). Soils are derived from massive accumulation of fine loess and alluvial sediments during the Quaternary (Pennington et al., 2000). The region presents a monsoonal climate with strong seasonality (dry winters, rainy summers) (Minetti, 1999), with high temperatures in summer and winter frosts. The average annual rainfall decreases in northeast-southwest direction from about 1000 to 400 mm y^{-1}. Potential