Radiation budget changes with dry forest clearing in temperate Argentina

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Abstract

Land cover changes may affect climate and the energy balance of the Earth through their influence on the greenhouse gas composition of the atmosphere (biogeochemical effects) but also through shifts in the physical properties of the land surface (biophysical effects). We explored how the radiation budget changes following the replacement of temperate dry forests by crops in central semiarid Argentina and quantified the biophysical radiative forcing of this transformation. For this purpose, we computed the albedo and surface temperature for a 7-year period (2003–2009) from MODIS imagery at 70 paired sites occupied by native forests and crops and calculated the radiation budget at the tropopause and surface levels using a columnar radiation model parameterized with satellite data. Mean annual black-sky albedo and diurnal surface temperature were 50% and 2.5 °C higher in croplands than in dry forests. These contrasts increased the outgoing shortwave energy flux at the top of the atmosphere in croplands by a quarter (58.4 vs. 45.9 W m^{-2}) which, together with a slight increase in the outgoing longwave flux, yielded a net cooling of -14 W m^{-2}. This biophysical cooling effect would be equivalent to a reduction in atmospheric CO_2 of 22 Mg C ha^{-1}, which involves approximately a quarter to a half of the typical carbon emissions that accompany deforestation in these ecosystems. We showed that the replacement of dry forests by crops in central Argentina has strong biophysical effects on the energy budget which could counterbalance the biogeochemical effects of deforestation. Underestimating or ignoring these biophysical consequences of land-use changes on climate will certainly curtail the effectiveness of many warming mitigation actions, particularly in semiarid regions where high radiation load and smaller active carbon pools would increase the relative importance of biophysical forcing.

Introduction

Although the effects of land cover changes on climate are now largely recognized, their influence on the atmospheric composition of greenhouse gases has received the greatest attention (Bonan, 2008; Anderson *et al.*, 2011). However, direct modifications of the physical properties of the surface by land cover changes have raised a growing concern in the last years because they may also influence climate trough their effects on the energy budget (Betts, 2000; Marland *et al.*, 2003; Betts *et al.*, 2007). These biophysical effects, which include changes in albedo, latent/sensible heat partition, and surface roughness, among others, have been less studied and understood, although a raising body of knowledge is recently emerging (Jackson *et al.*, 2008; Lohila *et al.*, 2010; Anderson *et al.*, 2011).

Unlike biogeochemical effects, which involve global processes and large time scales, biophysical ones usually manifest with fast or immediate reactions, at regional and/or local scales and may counteract or enhance biogeochemical processes (Anderson *et al.*, 2011). For instance, afforestation is a potentially important climate change mitigation strategy (Pacala & Socolow, 2004; Canadell & Raupach, 2008) however, its climatic benefits are more questionable when both biogeochemical and biophysical effects are considered (Jackson *et al.*, 2008; Anderson *et al.*, 2011). Modeling studies suggest that boreal deforestation has a significant cooling outcome because biophysical effects, mediated by a large albedo increase, are higher than biogeochemical ones (Betts, 2000; Bala *et al.*, 2007). By contrast, deforestation in the tropics has a net warming effect, as biogeochemical processes (i.e. change in carbon storage and uptake) are more important than the albedo change (Betts, 2000). In temperate regions, the effects of deforestation on climate have larger uncertainties since biophysical processes are poorly understood and the carbon balance is highly variable (Bonan, 2008). Particularly, the replacement of temperate dry forest by crops is of key relevance because of its areal

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expansion and large biogeochemical and biophysical contrasts between both vegetation covers (Betts *et al.*, 2007; Jackson *et al.*, 2008; Anderson *et al.*, 2011).

The replacement of forests by herbaceous vegetation involves large biophysical alterations that may affect the radiation budget with potential climatic effects at different spatial scales according to the extension of the land-cover change (Marland *et al.*, 2003). For instance, modeling experiments suggest that large scale land-use transformation, like a complete tropical or boreal deforestation, may impact climate well beyond the region where the transformation takes place (Bonan *et al.*, 1992; Werth & Avissar, 2002; Bala *et al.*, 2007). Regionally, spatial heterogeneities, resulting for instance from the alternation of forests and open lands, can generate differential heating of the surface altering mesoscale circulation and the regional climate (Pielke *et al.*, 1998; Durieux *et al.*, 2003). Small scale land-use changes (hectares) may also affect climate locally, as evidenced by meteorological measurements that show significant differences in the surface air temperature between grasslands and nearby forested lands (Lee *et al.*, 2011).

The change in surface albedo that usually accompanies deforestation is a key climatic aspect (Bonan, 2008; Beltrán-Przekurat *et al.*, 2011). Forests usually present lower albedo than crops (Ni & Woodcock, 2000; Gao *et al.*, 2005; Loarie *et al.*, 2010). As a consequence, the replacement of dry forests by crops would reduce the amount of shortwave (SW) solar radiation captured by the ecosystem, which would result in a cooling effect (Betts, 2000). On the other hand, forests have significantly higher canopy roughness and aerodynamic conductance than herbaceous vegetation (Kelliher *et al.*, 1993), which translates into a higher capacity to transfer heat, both latent and sensible, into the surrounding atmosphere (Jackson *et al.*, 2008), resulting in forest canopies usually cooler than herbaceous vegetation (Nosetto *et al.*, 2012a). As a consequence of higher surface temperatures in croplands, the replacement of dry forests by crops would increase the amount of outgoing longwave (LW) radiation leaving the earth-atmosphere system, causing an additional net loss of energy (Rotenberg & Yakir, 2010), besides the albedo-mediated one. The replacement of dry forests by crops may also affect the energy budget through more complex atmospheric effects. For instance, this land-use change may modify planetary albedo in different directions if the lower evapotranspiration of crops (Nosetto *et al.*, 2012a) translates into decreased cloud formation (Werth & Avissar, 2002) or if agricultural practices (e.g. harvesting, plowing, tillage, fallow periods) increasd wind erosion and dust aerosol formation (Houghton *et al.*, 2001; Betts, 2007).

The term 'radiative forcing' is usually used to describe any perturbation of the earth's radiation budget and is the standard measure for comparing qualitatively different effects on climate. Radiative forcing refers to the change in net (down minus up) irradiance (solar plus longwave) at the tropopause level and gives a measure of the global warming (or cooling) potential of any anthropogenic or natural forcing (Davin *et al.*, 2007; Forster *et al.*, 2007). According to the Fourth Assessment Report of the IPCC, the combined radiative forcing of all anthropogenic factors since 1750 is estimated to be $+1.6$ W m^{-2} (Forster *et al.*, 2007), suggesting a likely human influence on the global warming trend. Global estimates suggest that land cover changes, particularly through forest cover reduction, produce a net positive forcing in which CO_2 emissions approaching $+0.4$ W m^{-2} exceed the opposing effect of surface albedo increase of -0.2 W m^{-2} (Forster *et al.*, 2007). These values refer to global means and do not account for the large spatial variability that both biogeochemical and biophysical forcings can have depending on where land-use changes take place. For instance, the albedo decrease caused by an hypothetical replacement of all agricultural lands by forests in the northern hemisphere would lead to local radiative forcings that range from $+3$ W m^{-2} in temperate regions to $+20$ W m^{-2} in boreal areas (Betts, 2000). In this article, we used the radiative forcing concept to estimate the perturbation on the radiation budget originated by the replacement of native forests by crops. We focused in semiarid areas which, compared to humid ones, have higher insolation and smaller active carbon pools, which may increase the relative importance of biophysical vs. biogeochemical forcing effects of the land-use changes that they host.

Globally, forests are being intensively cleared and under high conservation risk (Hoekstra *et al.*, 2005). Although in South America, changes in the Amazon receive the greatest attention, extra-tropical deforestation for grain and forage production is also increasing, becoming the most important land cover changes in the last decades (Kaimowitz & Smith, 2001; Morton *et al.*, 2006; Gasparri & Grau, 2009). Increased rainfall, socioeconomic changes (e.g. better transport infrastructure, international markets) and technological improvements have been the main causes for these transformations (Grau *et al.*, 2005). In Argentina, the area covered by annual crops increased at a rate of 0.27% yr^{-1} between 1988 and 2002 (Paruelo *et al.*, 2006), with 25 million hectares now devoted to the production of rain-fed soybeans, wheat, maize, and other grains where dry forests used to be the dominant vegetation. In the most cultivated areas, deforestation rates approached 2.2% yr^{-1} in the last 30 years,

being one of the highest on the globe (Zak *et al.*, 2004). Large areas of natural and seminatural dry forests with suitable environmental conditions for rain-fed agriculture (Grau *et al.*, 2005) are still present in Argentina, Bolivia and Paraguay, but the increasing global demand for food products is putting them under higher pressure.

In this article, we characterized the seasonal patterns of surface albedo and temperature in native dry forests and crops of temperate Argentina and we quantified, through remote sensing and radiative modeling, the alterations on the radiation budget associated with this transformation. We quantified the radiation budget at the surface and tropopause levels for both covers and computed the radiative forcing associated with changes in surface albedo and temperature caused by the replacement of dry forests by crops. Complementarily, we assessed the seasonal dynamic of NDVI for both covers as a surrogate of primary productivity and leaf area seasonality. We chose 70 sites occupied by native dry forests and grain crops in central Argentina (Fig. 1) (San Luis, La Pampa and Córdoba provinces) and characterized the seasonal pattern of albedo, surface temperature and NDVI for a period of 7 years (2003–2009) based on remote information from MODIS sensors on board of Terra and Aqua satellites. A column radiation model was used to compute the radiation budget at the surface and tropopause levels.

Materials and methods

Study region

We performed this study in the dry forest area of San Luis, Córdoba and La Pampa provinces in central Argentina (Fig. 1), between latitudes −31.09 and −36.36 and longitudes −66.03 and −64.60. The area has a gentle topography and a temperate semiarid climate with a mean annual temperature varying between 16.5 and 18 °C (Period 1960–1990, New *et al.*, 2002). January and July are the hottest and coldest months with 24 and 9 °C, respectively, and snowfalls are rare. Mean annual precipitation increases from west (~550 mm yr^{-1}) to east (~650 mm yr^{-1}) of the study region, and is mainly concentrated in spring and summer (80%) (Period 1960–1990, New *et al.*, 2002). For the study period (2003–2009), annual rainfall registered in a meteorological station located close to the center of our study region varied between 430 and 900 mm yr^{-1} and averaged 700 mm yr^{-1}. For the same period, the annual temperature averaged 16.4 °C. During the last century rainfall increased by 30% in the region, with the fastest increase taking place between 1970 and 2000 (Giuletti *et al.*, 2003). Potential evapotranspiration varies between 1200 and 1500 mm yr^{-1}. Soils are coarse textured and developed from loessic materials. Mollisol and Entisols are the dominant soil orders and they do not present significant constraints for crop production (Inta-Sagyp, 1990).

The study region is located in the transition zone between the Espinal and Chaco phytogeographycal districts (Cabrera, 1976). Both districts are characterized by dry forests dominated by short leguminous trees (<8 m of height). *Prosopis*
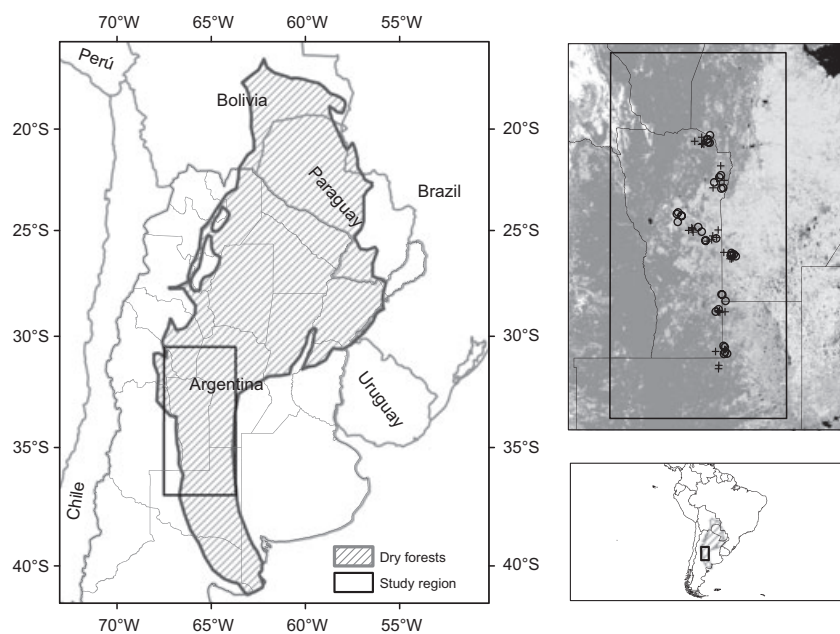

Fig. 1 Location of the study region showing the distribution of the study sites. The original dry forest area is indicated with the striped pattern. Dry forest sites (black crosses) and cropland sites (open circles) are indicated on the top-right image. The current dry forest and cropland distribution in the region is indicated with dark and light gray, respectively, based on Eva *et al.* (2004).

caldenia, *Prosopis flexuosa* and *Geoffroea decorticans* are the dominant tree species in the Espinal district, whereas *P. flexuosa* and *Aspidosperma quebracho blanco* dominate the fraction of the Chaco district that we studied. Depending on their fire and grazing history, among other causes, these regions can be occupied by open savannas or closed woodlands (Dussart *et al.*, 1998). The shrub cover is dominated by *Condalia microphylla*, *Capparis atamisquea*, and *Larrea divaricata* among other species, and grasses and forbs occupy the understory. The region is now experiencing fast deforestation rates for crop production, motivated in part by the expanding global soybean market, technological improvements, and increasing rainfall (Paruelo *et al.*, 2006). Nowadays, 40% of the original dry forest area has been cleared, with deforestation rates approaching 20 000 ha yr^{-1} during the last decades (Collado & Houspanossian, 2009). Soybean is the prevailing crop in the region, yet corn, sunflower, wheat, and rye are cultivated as well. Currently, remaining patches of native dry forests persist embedded in a widespread agricultural matrix.

Satellite processing and the radiation budget

To evaluate the effects of dry forest clearing for crop production on the radiation budget, we selected 70 sites completely occupied by native dry forests (*n* = 35) or crops (*n* = 35). All selected sites were larger than 3 × 3 km. To ensure that our sampled pixels were fully occupied by a unique land-cover type (dry forest or crop) we used core pixels at each site excluding a ~1 km-wide edge zone. Site definition was based on high resolution Google Earth images and field observations. Average plot sizes in the region are ~200 and ~1700 ha for croplands and dry forests, respectively.

For the period 2003–2009, we used the albedo, surface temperature, and NDVI products from MODIS sensors to characterize their seasonal patterns in dry forests and crops. We used the MCD43A3 (albedo), MOD13Q1 (vegetation index), and MOD11 and MYD11 (surface temperature) products. MOD13Q1 and MCD43A3 products derive from the daily surface reflectance product (MOD09 series), corrected for molecular scattering, ozone absorption, and aerosols (Vermote *et al.*, 2002). The albedo product represents an 8-day composite with a spatial resolution of 500 m and combines reflectance data from Terra and Aqua satellites to compute, through the integration of a bidirectional reflectance distribution function, the black-sky albedo and white-sky albedo in seven spectral narrow bands and three broadbands [visible (VIS) 0.3–0.7 μm, near-infrared (NIR) 0.7–5.0 μm and SW 0.3–5.0 μm]. The black-sky albedo represents the directional-hemispherical reflectance, which operates under direct illumination (no diffuse component). The white-sky albedo represents the bi-hemispherical reflectance and operates under diffuse illumination (no direct component). Actual albedo for a particular atmospheric and illumination condition can be computed from the fraction of diffuse radiation and black- and white-albedo components (Schaaf *et al.*, 2002). Albedo products from MODIS have been thoroughly validated with field observations and other satellite data (Tsvetsinskaya *et al.*, 2006). The MOD11 and MYD11 products derive from Terra and Aqua

satellites, respectively, where surface temperature is retrieved using the generalized split-window algorithm with two thermal bands (Wan, 1999). These products have a spatial resolution of 1 km, integrate a 8-day period and their accuracy is reported to be 1 °C (Wang *et al.*, 2008). The NDVI index, which has proved to be highly correlated with net primary productivity and leaf area index (Paruelo *et al.*, 1998a), was obtained from the MOD13Q1 product from the Terra satellite with a temporal integration of 16 days and a spatial resolution of 250 m. To ensure a high quality of MODIS pixels, we performed a filtering based on the quality bands of MODIS products (Justice *et al.*, 1998). MODIS data were downloaded from NASA's Earth Observing System (http://reverb.echo.nasa.gov/reverb/).

To estimate the radiation balance in dry forests and crops, and particularly the difference between both covers, we used a Column Radiation Model (CRM) (Briegleb, 1992; Randerson *et al.*, 2006), which is a stand-alone version of the radiation model used in the NCAR Community Climate Model. Two sets of runs were performed, one for dry forests and the other one for crops sites. In both cases, we parameterized the ground surface with biophysical data (albedo and surface temperature) obtained from MODIS sensors. To capture both diurnal and seasonal variations in solar geometry, the runs were performed hourly and integrated over the day, every 8 days and for a period of 7 years (2003–2009). We assumed a constant albedo value along the day (Myhre *et al.*, 2005) and we estimated the hourly surface temperature based on a sinusoidal function adjusted with MODIS measurements at 00:00, 02:00, 12:00, and 14:00 hours, local time. It is important to highlight that latent and sensible heat fluxes are not estimated by the CRM. For all the simulations, we used monthly mean profiles of atmospheric temperature, specific humidity, ozone concentration, cloud cover, and cloud liquid water content from the European Centre for Medium-Range Weather Forecasts 40 years Reanalysis product (Myhre *et al.*, 2005; Uppala *et al.*, 2005; Dee *et al.*, 2011). The average aerosol optical depth was estimated to be 0.07 based on the 550 nm aerosol band from MODIS MOD08 Aerosol product (Remer *et al.*, 2005). The results of the radiation budget are presented for the tropopause and surface levels, which correspond to the 200 and 1000 mb pressure levels in the model, respectively. For both pressure levels, we estimated the radiative forcing as the difference in the outgoing radiation flux (shortwave and longwave) between croplands and native dry forests.

To compare the radiative forcing associated with albedo and surface temperature changes, we calculated the amount of carbon that would need to release as CO_2 into the atmosphere to produce a similar radiative forcing. We calculated the local contribution of a hectare that is deforested to global radiative forcing by dividing our radiative forcing estimate at the top of the atmosphere by the earth's surface area (Betts, 2000). We used a radiative forcing efficiency of 5.35 (Myhre *et al.*, 1998) to relate the previous estimate to the change in carbon stock through the following relationship.

$$RF = 5.35\ln(1 + \Delta C/C_0) \qquad (1)$$

where C_0 is the present day CO_2 concentration (385 ppmv, Menon *et al.*, 2010) and ΔC is the globally averaged

atmospheric CO_2 change that would be required to produce a certain global radiative forcing, which is related to terrestrial carbon stock change ΔC_t through the expression:

$$\Delta C_t = 2(M_c/M_a)m_a(\Delta C/C_0) \quad (2)$$

where M_c and M_a are the molecular mass of carbon and dry air, m_a is the mass of the atmosphere, and the factor of 2 accounts for an airborne emissions fraction of 0.5 (Schimel *et al.*, 1995).

Results

Albedo, surface temperature, and NDVI patterns

Croplands showed consistently higher albedo values than native dry forests along the 7-year period of analysis (Fig. 2a). On average, the replacement of dry forests by crops increased the black-sky albedo by 50% (0.160 and 0.108 for crops and dry forests, respectively, $P < 0.05$). Both vegetation covers showed low seasonal variation throughout the year, with monthly albedo values varying between 0.153 and 0.164 in crops and between 0.105 and 0.112 in dry forests (Fig. 2a). Albedo differences between crops and dry forests were always significant ($P < 0.05$) and ranged from 0.055 for winter months to 0.047 for summer months (Fig. 3a). Mean annual albedo showed low interannual variation, principally in dry forests, where it varied between 0.107

and 0.110; whereas in crops it varied between 0.154 and 0.171. Albedo variation across sites was similar in both vegetation types and ranged from 0.095 to 0.122 in dry forests and from 0.147 to 0.178 in croplands.

A large albedo peak (~0.2) was observed during April–May 2009 in croplands, but not in dry forests (Fig. 2a). Likely, the severe drought that took place in February–May 2009, with less than 20% of the average rainfall for that period, may have decreased the capacity of active crops to absorb photosynthetic active radiation (Zygielbaum *et al.*, 2009; Kim *et al.*, 2011), with a consequent increase in the SW albedo (24% above the average). This agreed with an observed larger increase in the visible albedo (35% above the average), which is more functionally related with the activity of leaf pigments, than in the NIR albedo (17% above the average), which is more related with the physical structures of vegetation leaves (Jones & Vaughn, 2010). A similar, but smaller, albedo peak was observed during May 2008, in coincidence with a less severe drought during March–April 2008 when rainfall was 50% below average.

Although croplands absorbed less solar radiation because of their higher albedo compared to dry forests, they presented significantly higher daytime surface temperature throughout the year. On average, the surface temperature registered by MODIS sensors at 12:00
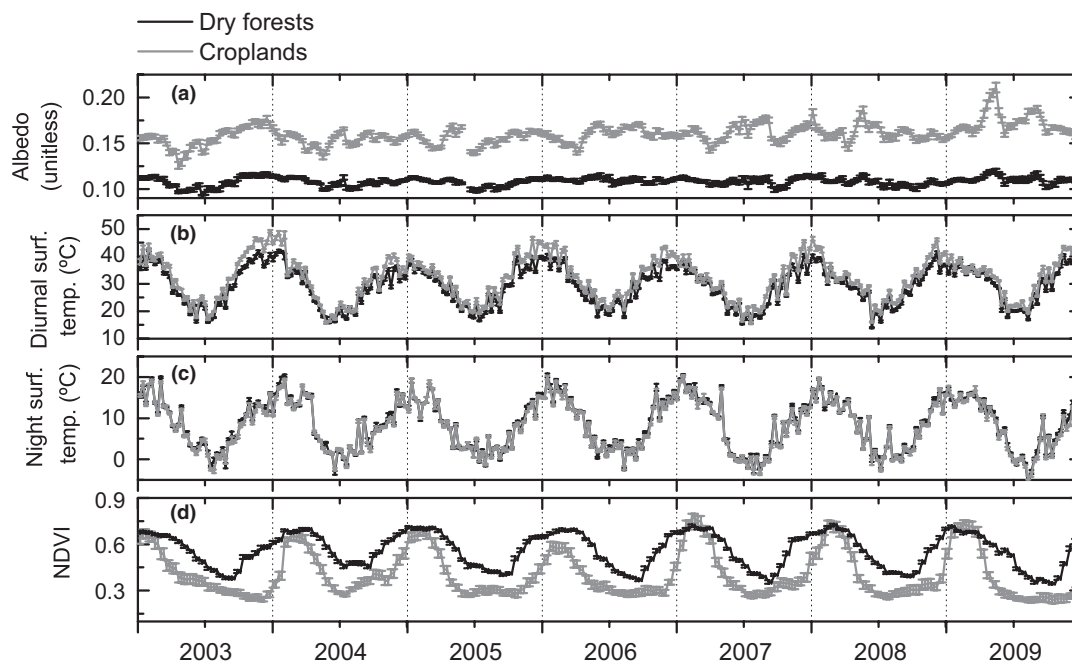

Fig. 2 Temporal series of surface albedo (a), diurnal surface temperature (b), nocturnal surface temperature (c), and NDVI (d) of dry forests (average for 35 sites, black line) and croplands (average for 35 sites, gray line). Data were derived from MODIS sensors on board of Terra and Aqua satellites and its frequency is 8 days for all variables except NDVI which is 16 days. Bars correspond to standard deviation.
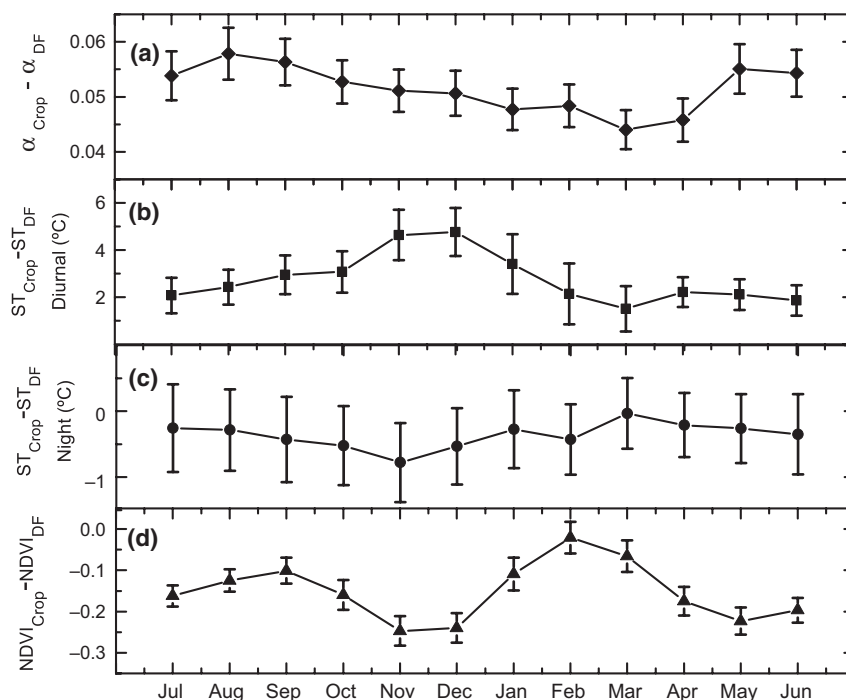
Fig. 3 Temporal series of the monthly differences between dry forests and croplands in surface albedo (a), diurnal surface temperature (b), nocturnal surface temperature (c), and NDVI (d). Bars correspond to standard deviation. Monthly values were averaged from a period of 7 years.

and 14:00 hours was 2.5 °C higher in croplands than in dry forests (29.7 and 27.2 °C for crops and dry forests, respectively, $P < 0.05$) (Fig. 2b). By contrast, no significant differences were observed for nocturnal surface temperatures registered at 00:00 and 02:00 hours ($P > 0.1$) (Fig. 2c). Maximum differences in diurnal surface temperature between both vegetation covers were observed during spring months (Fig. 3b) (4.5 and 5 °C for November and December, respectively), likely responding to sharp phenological contrasts, as dry forests had already started their growing season, presenting fully developed leaves at that time of the year, whereas summer crops were just being established or going through their initial growth stages. In the opposite way, minimum differences were observed during summer months (2.1 and 1.6 °C for February and March, respectively) (Fig. 3b), corresponding to the period of full biomass development in crops. During winter months, when trees have an almost complete lack of leaves, particularly in the Espinal vegetation, forests were still 2.5 °C cooler than fallow land in croplands, suggesting that cooler surfaces in forests are not only the result of active canopies but of other less seasonal structural attributes (e.g. high branch density and height) that enhance sensible heat fluxes.

The NDVI, a surrogate of primary productivity and water use by vegetation, was on average 35% higher in dry forests than in crops (0.56 and 0.41 for dry forest and crops, respectively, $P < 0.05$) (Fig. 2d). Although both covers showed relatively synchronous seasonal patterns, with maximum values in summer and minimum in winter, dry forests showed a smoother seasonal curve. Croplands had lower winter values and sharp NDVI peaks that exceed the NDVI of dry forests in few occasions (Fig. 2d). Matching diurnal surface temperature contrasts, maximum NDVI differences were observed in spring (0.56 and 0.34 for dry forests and crops, respectively, $P < 0.05$) and minimum in summer (0.68 and 0.62 for dry forests and crops, respectively, $P < 0.05$) (Fig. 3d). Annual NDVI varied among sites between 0.50 and 0.64 in dry forests and between 0.35 and 0.49 in croplands.

The NDVI was highly associated with the SW albedo, but surprisingly, the relationship was opposite for both vegetation types (Fig. 4a). Although in croplands higher NDVI values were associated to higher albedo ($r^2 = 0.37$, $P < 0.05$, $n = 35$), in dry forests, NDVI and albedo were inversely associated ($r^2 = 0.44$, $P < 0.05$, $n = 35$) (Fig. 4a). To analyze this singular pattern in greater detail, we evaluated the relationship between NDVI and visible (VIS) and near-infrared (NIR) albedo. In dry forests, NDVI was inversely associated with both VIS and NIR albedo (Fig. 4c, d) indicating that forests with higher productivity, and most likely well preserved conditions and higher overall woody biomass,
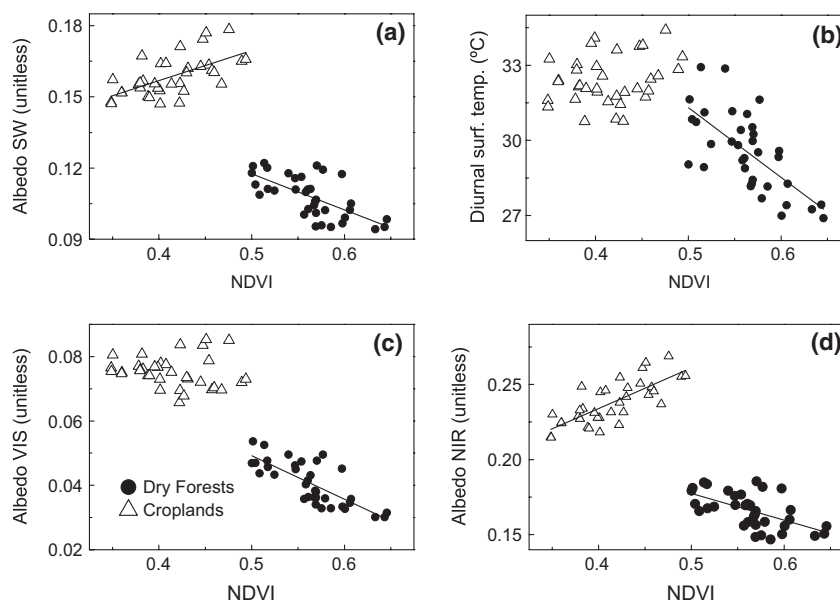
Fig. 4 Relationships between NDVI and: shortwave albedo (a), diurnal surface temperature (b), visible albedo (c), and near-infrared albedo (d) for dry forests and croplands. Each point represents the mean annual value of each site. Lines adjust significant linear relationships between variables ($P < 0.05$).

absorbed more solar radiation. By contrast in croplands, the NDVI showed a positive and close association with NIR albedo ($r^2 = 0.55$, $P < 0.05$) (Fig. 4d), but no relationship with VIS albedo ($r^2 = 0.01$, $P > 0.1$) (Fig. 4c). Furthermore, higher NDVI values were associated with lower surface temperatures in dry forests ($r^2 = 0.46$, $P < 0.05$, Fig. 4b), despite decreasing albedo values (Fig. 4a), suggesting an increasing capacity to dissipate sensible and/or latent heat. No significant relationship was observed between NDVI and surface temperature in croplands ($r^2 = 0.05$, $P > 0.1$).

Radiation budget and climatic forcing

Monthly outgoing radiation flux at the surface and tropopause levels showed consistent differences between dry forests and croplands, more clearly evident for the SW flux (Fig. 5). At the tropopause level, the annually averaged outgoing SW flux approached 45.9 W m^{-2} in dry forests and 58.4 W m^{-2} in croplands ($P < 0.05$) (Fig. 5a). Maximum and minimum values were observed for both covers during December (62 and 80 W m^{-2}, for dry forests and croplands) and June (29 and 36 W m^{-2}, for dry forests and croplands), respectively. The annually averaged outgoing LW flux showed lower, but statistically significant differences between both vegetation covers and approached 289.6 W m^{-2} in dry forests and 291.1 W m^{-2} in croplands ($P < 0.05$) (Fig. 5c). Contrasts were more evident during November and December when the difference

between both vegetation types was 2.35 W m^{-2} ($P < 0.05$). Maximum differences in the outgoing LW flux at the top of the atmosphere of 6 W m^{-2} were registered during the very dry spring of 2003, when croplands showed diurnal surface temperatures up to 7 °C higher than dry forests.

At the surface level, statistical differences between both covers remained for the SW flux and increase in LW flux when compared to the tropopause level ($P < 0.05$) (Fig. 5b, d). The annually averaged outgoing flux approached 41 W m^{-2} in croplands and 27 W m^{-2} in dry forests for the SW component (Fig. 5b), and 417 W m^{-2} in croplands and 410 W m^{-2} in dry forests for the LW component (Fig. 5d).

The radiative forcing resulting from the replacement of native dry forests by crops showed a clear cooling effect, which averaged −14 W m^{-2} at the tropopause level (Fig. 6a) and would be equivalent to a reduction in CO_2 of 22 Mg C ha^{-1}. Although the albedo increase was the main contributor to this outcome (90%), the increase in the surface temperature produced an additional cooling effect of −1.5 W m^{-2} because of an increased outgoing LW flux. Monthly radiative forcing varied from minimum values in winter (−9 W m^{-2}) to maximum ones during summer months (−18 W m^{-2}), mainly following the solar irradiation pattern. When changes in outgoing radiation were considered at the surface level, a radiative forcing of −20 W m^{-2} was found with SW and LW contribution being 70% and 30%, respectively (Fig. 6b).
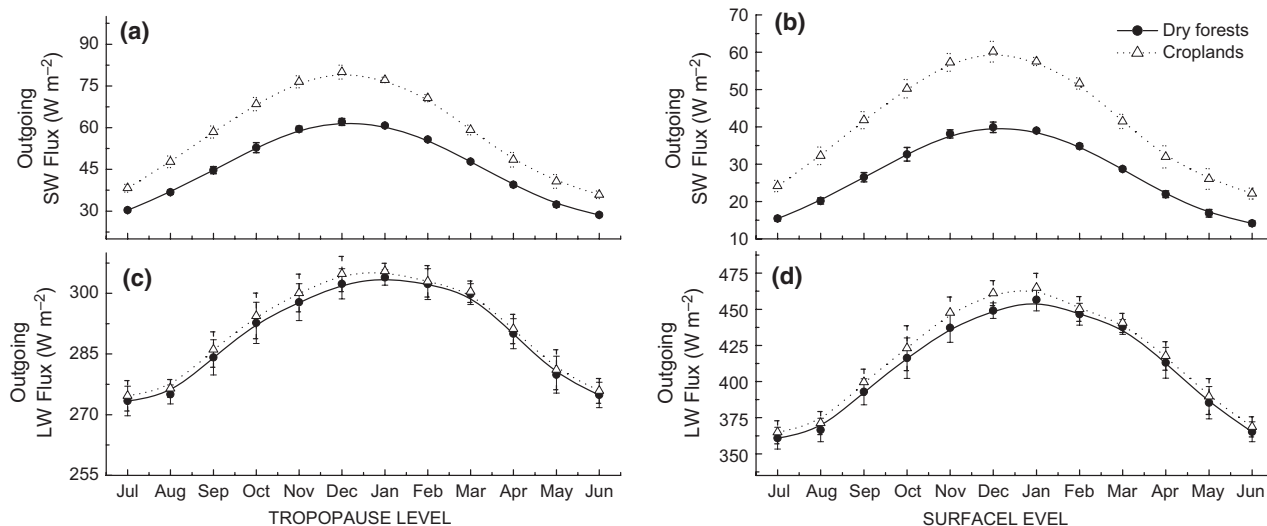
Fig. 5 Mean monthly outgoing shortwave (SW) and longwave (LW) fluxes at the tropopause [(a) and (c), respectively] and surface [(b) and (d), respectively)] levels for dry forests (triangles) and croplands (black points). Bars correspond to standard deviation. Monthly values were averaged from a period of 7 years.
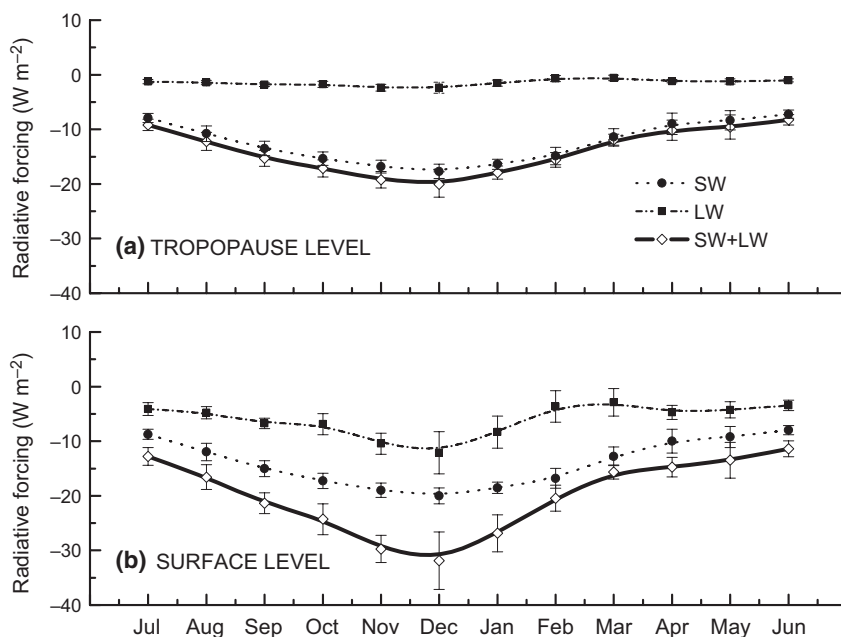

Fig. 6 Radiative forcing (RF) by albedo and surface temperatures changes at the tropopause (a) and surface (b) levels. Monthly averaged radiative forcings (in W m^{-2}) are presented for the shortwave (SW), longwave (LW), and the sum of both components. The radiative forcing was calculated as the difference in radiative fluxes between vegetation covers (croplands – dry forests). Bars correspond to standard deviation.

Discussion

The replacement of temperate dry forests by crops in central Argentina has strong biophysical effects on the energy balance at the surface and tropopause levels. We showed that deforestation of dry forests increased markedly the surface albedo and because of this, the radiation escaping from the earth-atmosphere system resulted augmented by 30%. However, despite of a higher absorption of solar radiation caused by a lower albedo, the dry forests exhibited significantly cooler canopies than croplands. These findings imply, on the

one hand, that the warming effects of deforestation associated with the carbon cycle could be at least partially counterbalanced by the cooling effects of albedo changes. On the other hand, the cooler surfaces of dry forests imply an increased capacity for heat dissipation through both sensible and latent heat fluxes which resulted diminished after deforestation.

The biophysical cooling effect associated to deforestation of temperate Argentinean dry forests is consistent with modeling and observational studies performed in other regions worldwide (Nair *et al.*, 2007; Rotenberg & Yakir, 2010). On the basis of satellite information from the Clouds and the Earth's Radiant Energy System, Nair *et al.* (2007) estimated a radiative forcing of -14 W m^{-2} for the transition from woody savanna to croplands in Southwest Australia. These authors suggested that the seasonal trends of radiative forcing were explained by crop management practices, whereas we found them more closely related to the solar radiation seasonality (Fig. 6). Simulations with the radiative transfer scheme HadAM3 suggest that the opposite land-use change, that is the conversion of croplands into coniferous plantations, would have positive albedo forcings of $+3$ to $+10$ W m^{-2} in temperate regions and over $+20$ W m^{-2} in boreal regions due to the strong albedo differences under snow covered surfaces (Betts, 2000). In the same line, successive fires in boreal forest are suggested to lead to net cooling because closed canopies shifted to open woodlands with a large albedo increase (Bernier *et al.*, 2011). However, recent studies, based on more realistic land-use change scenarios, suggest that reforestation of formerly deforested areas would have a net cooling effect (Montenegro *et al.*, 2009; Pongratz *et al.*, 2011). Rotenberg & Yakir (2010) estimated from field tower observations a radiative forcing of $+49$ W m^{-2} at the surface level for the afforestation of a sparse shrubland with pines in southern Israel. This high radiative forcing estimate, which more than doubles our surface level figures, could be explained by both larger albedo contrasts between vegetation covers (0.1 vs. 0.05) and higher radiation loads ($+15\%$) at the Israeli site.

The strong biophysical cooling brought by deforestation arises from the combination of large differences in surface albedo between forests and crops and the low cloudiness and high solar radiation of their semiarid environment, which exacerbate net albedo effects at the top of the atmosphere. The strong albedo contrast is favored by the extremely low values of dry forests (0.11, Fig. 2a), which to our knowledge are among the lowest being reported in the literature (Schaeffer *et al.*, 2006; Jackson *et al.*, 2008). It is interesting to highlight that maximum albedo differences were observed dur-

ing winter, when most of the dry forests that we studied have lost their leaves (Fig. 3). Likely, the very dark bark of these forests, together with high branch densities and heights, lead to high capture of direct and ground-reflected solar radiation, explaining the overall low albedo (Shaharuddin & Lockwood, 1979; Rotenberg & Yakir, 2011). The negative relationship between NDVI, a surrogate of vegetation productivity and of standing biomass (Paruelo *et al.*, 1998b), and NIR albedo (Fig. 4) in dry forests, but not in croplands, provides support to this notion. Reflectance in the NIR portion has proved to be highly and positively related with green leaf biomass (Gamon *et al.*, 1995), as we observed in croplands (Fig. 4d). In dry forest, however, increasing vegetation productivity is likely associated to higher standing wood amounts absorbing much more NIR radiation than leaves (Gamon *et al.*, 1995).

In spite of absorbing more solar radiation, dry forests kept their canopies significantly cooler during daytime than crops (Fig. 3b), which translates into lower LW emission. This pattern, already documented in other native dry forests of the region (Nosetto *et al.*, 2012a) and tree plantations (Nosetto *et al.*, 2005; Rotenberg & Yakir, 2010), denotes the enhanced capacity of trees canopies to dissipate heat into the atmosphere, likely due to their higher aerodynamic conductance (Kelliher *et al.*, 1993). Seasonal analysis of surface temperatures suggests that both latent and sensible heat fluxes operate simultaneously cooling forest canopies. During winter, dry forests were able to keep their canopies 2.5 °C cooler than croplands despite absorbing 11 W m^{-2} more, almost exclusively because of sensible heat dissipation as evapotranspiration is a minor component of the energy balance in that period in both vegetation covers, as suggested by satellite estimates (Nosetto *et al.*, 2012b) and eddy covariance measurements (Garcia *et al.*, in preparation). During spring months (October and November) and after the onset of the rainy season, forests canopies were 4 °C cooler than croplands despite absorbing an even higher load of solar radiation of 22 W m^{-2}. In this case, higher latent heat fluxes, in addition to sensible heat fluxes, would be helping to cool forest canopies as evapotranspiration is significantly higher in dry forests than that in crops during this period (Nosetto *et al.*, 2012b). As a general picture, regional estimates of heat fluxes based on a coupled vegetation-atmospheric modeling suggests similar sensible and heat fluxes of 60–80 W m^{-2} in summer in our study region, and fluxes of 20–40 and 0–20 W m^{-2} in winter for the latent and sensible heat components, respectively (Dan *et al.*, 2005). In contrast to the temperature differences observed during daytime, no significant differences were observed between crops and dry forests for the nocturnal surface tempera-

tures. Likely, higher heat storage in the forest biomass than that in crops helped to keep forest canopies warmer at night (Michiles & Gielow, 2008; Adams, 2010; Lindroth *et al.*, 2010).

Besides the albedo effect on the SW radiation balance, the differences in heat dissipation between both covers may produce additional consequences on the climatic system since a large amount of energy that forests dissipate into the atmosphere as heat fluxes, would be transferred as LW radiation in a deforested surface. On the one hand, the extra heating of cropland surfaces (Fig. 3b) may alter local air temperatures and circulation patterns with potential consequences on local climate (Pielke & Avissar, 1990). In addition, the evapotranspiration decrease with deforestation has also the potential to alter local climate through water balance- and energy balance-mediated effects (Entekhabi *et al.*, 1996; Eltahir, 1998). Firstly, evapotranspiration is the main source of atmospheric moisture, particularly in arid and semiarid areas, where recycled precipitation accounts for a large proportion of total rainfall (Savenije, 1995). Secondly, the diminished latent (and sensible) heat flux over crops decreases the moist static energy of the boundary layer, which may impact on moist convection and consequently on local convective storms (Eltahir, 1998). Several studies, especially in tropical regions, show that forests play a major role on atmospheric circulation and water cycling (Lean & Warrilow, 1989; Durieux *et al.*, 2003; Makarieva *et al.*, 2009), however, if dry forest deforestation in southern South America will have a noticeable impact on local rainfall is still uncertain, but likely according to moisture recycling estimates based on climate reanalysis data (Van Der Ent *et al.*, 2010). Modeling exercises, satellite observations, and climatic trend analysis may all help to uncover this issue.

The net climate forcing resulting from the replacement of dry forests by crops becomes hard to anticipate when both biophysical and biogeochemical effects are considered. This uncertainty is not only the result of the opposing signs of these two types of effects but also of the variable conservation stages of native forests, which affect not only their carbon pools and uptake but their albedo and energy dissipation rates. The few existing biomass carbon budgets for dry forests in the study region indicate total (above and belowground) carbon stocks of 49–81 Mg C ha^{-1} (Bonino, 2006; Kim, 2011). According to the previous numbers and our radiative forcing estimates, the biogeochemical effect of dry forests deforestation would overcome the biophysical effect mediated by the albedo increase. However, between a quarter and nearly a half of the heating effect of carbon release from forest biomass could be offset by the albedo change after deforestation. Soil carbon

changes with deforestation are even more uncertain, with some studies showing no changes (Bonino, 2006; Kim, 2011) and other suggesting a reduction of up to 38 Mg C ha^{-1} (Kim, 2011). Besides the uncertainty of net carbon release at the plot level, those related to its fate at the global scale are also important, since almost half of the current CO_2 emissions are absorbed by the oceans and land surfaces (Schimel *et al.*, 1995). Although deforestation of Argentine dry forests may certainly have a strong impact on climate because of large carbon emissions (Gasparri *et al.*, 2008), our results suggest that the inclusion of the albedo forcing effect in the calculations could offset a significant fraction of the carbon emission forcing. The previous results also highlight the importance of having better estimates of carbon stocks and changes after deforestation to have more accurate estimates of the net radiative forcing.

Although biophysical forcings are usually ignored in current climate change mitigation strategies (Jackson *et al.*, 2008), we showed that the albedo increase triggered by forest clearing in a semiarid temperate region may neutralize a large part of the heating effects of carbon emissions. Although previous work downplayed albedo effects in areas outside boreal regions (Betts, 2000; Bala *et al.*, 2007), our work and others recently published (Rotenberg & Yakir, 2010) clearly demonstrate that these effects may be also significant in temperate dry regions, which cover an important fraction of the continental surface of the planet. This arises because of a large albedo change, high solar radiation load, and relatively low biomass stock. Besides the albedo-mediated effects on the radiation budget, we also showed that additional and less understood biophysical consequences are expected with deforestation because of the alteration of surface heat fluxes, which may further impact the local climate. Underestimating or ignoring the biophysical consequences of land-use changes on climate will certainly curtail the effectiveness of those warming mitigation actions that are centered on the expansion (e.g. afforestation) or conservation (e.g. REDD mechanism) of certain land covers.

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