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The net carbon drawdown of small scale afforestation from satellite observations

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ABSTRACT

Climate models indicate that warming due to increase in shortwave absorption from the lowering of albedo caused by afforestation reduces and can even overcome, particularly at high latitudes, the cooling caused by the carbon drawdown. We use high resolution ($0.05\times0.05°$ to $1\times1°$) global satellite observations to investigate the effects of afforestation. Results are markedly different from the coarser ($\sim2.5\times\sim2.5°$) model-based studies. Between 40°S and 60°N afforestation always results in cooling. Many of the areas with the highest net carbon drawdown (drawdown after albedo effects) are at high latitudes. There is large zonal variability in drawdown and latitude is not a good indicator of afforestation efficiency. The overall efficiency of afforestation, defined as the net carbon drawdown divided by the total drawdown, is about 50%. By only considering the total drawdown and not considering albedo effects, the Kyoto Protocol carbon accounting rules grossly overestimate the cooling caused by afforestation drawdown.

1. Introduction

Afforestation, the human induced conversion of crop or marginal lands into forests, is considered by the IPCC as one of the key climate change mitigation strategies available to the forestry sector (Nabuurs et al., 2007). The United Nations Framework Convention on Climate Change (UNFCC), through the Kyoto Protocol (UNFCCC, 2001), allows the atmospheric carbon drawdown generated by afforestation to be accounted as sequestered carbon and contributes to the emission budget of the signatory nations.

Surface reflectivity (or albedo) depends on land cover. Croplands tend to be brighter and hence absorb a smaller fraction of the incoming solar radiation than forests which tend to be darker. A change in vegetation will, through the associated albedo change, modify the local radiation budget. It is estimated that the increase in albedo caused by deforestation since 1750 has had a cooling effect with an average global negative radiative forcing of a $-0.2\ \mathrm{W\,m^{-2}}\pm 0.2\ \mathrm{W\,m^{-2}}$ (Solomon et al., 2007a).

In order to determine the climatic effects of afforestation, the cooling resulting from the sequestered carbon should be “discounted” by the warming induced by the decrease in surface albedo as land cover changes from crop to forest (Betts, 2000). This effect has been shown to be particularly important at higher latitudes because snow covered open lands have much higher albedo than snow covered forests.

In general, afforestation promotes greater evapotranspiration leading to an increase in latent heat flux and cooling (Kleidon et al., 2000; Govindasamy et al., 2001; Bounoua et al., 2002; Bala et al., 2007). Unlike the changes in albedo and atmospheric CO_2, this direct cooling is a local effect which does not significantly influence the planet's radiative budget (as the extra latent heat leaving the surface will be returned to the atmosphere as the vapour condenses). We use satellite derived evapotranspiration to estimate this local change.

Changes in evapotranspiration can affect the global radiative budget by their impacts on cloud cover and hence atmospheric albedo. This can be an important factor in the climate response to large scale land cover change, particularly in the lower latitudes (Betts et al., 2007), and an increase in cloud cover (and albedo) is predicted by models over afforested regions (Bala et al., 2007). The picture is not so clear for changes at smaller scales. For spatial scales ranging from 10^6 to $10^7\ \mathrm{m}^2$ (10 to 100 ha), observations indicate that a decrease in convection and cloud cover is to be expected over the afforested area (Rabin and Martin, 1996; Gash and Nobre, 1997; Durieux et al., 2003; Chagnon et al., 2004) and recent satellite data analysis over the tropics show no consistent difference in cloud coverage between nearby forested and deforested areas (Mulligan, 2008). Here we use global cloud observations with $25\ \mathrm{km}^2$ resolution to analyze the relation between cloud and surface cover.

In a study that used modelled albedo and observed regional estimates of potential sequestration, afforestation resulted in cooling at mid-latitudes and net warming in some high latitude areas (Betts,

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2000). In earlier studies using climate models, the global temperature response is cooling for low latitude afforestation, negligible change or warming for mid-latitude afforestation and warming for afforestation at high latitudes (Claussen et al., 2001; Gibbard et al., 2005; Bala et al., 2007).

The present UNFCC regulations on afforestation do not take the albedo effect into consideration (UNFCCC, 2001). According to the IPCC, while albedo effects should be taken into account, there are knowledge gaps on how the change in albedo will impact mitigation by afforestation (Nabuurs et al., 2007). Here we quantify the most relevant climatic effects of afforestation using high resolution satellite derived shortwave radiation flux, albedo, evapotranspiration, land cover, cloud cover and snow cover data.

Previous studies on this theme were either based on global climate models (Claussen et al., 2001; Gibbard et al., 2005; Bala et al., 2007) or required some input from global models (Betts, 2000). They were unable, due to their relatively coarse spatial resolution ($\geq 2\times 2°$), to provide results at a spatial scale relevant to individual afforestation projects. The models simulate afforestation by changing the cover globally or in whole latitude bands. These experiments are able to bracket the effects of maximum afforestation and provide information on the climatic process influenced by large scale change in vegetation cover, but they do not offer a realistic representation of how afforestation could occur. Even if afforestation becomes a very prominent mitigation tool, significant portions of present agricultural land would have to remain as such in the foreseeable future. Also, with the exception of (Betts, 2000), land cover is changed in areas where presently no crops are found, that is, the effects of afforestation are being considered over areas where no afforestation is possible.

Our analysis is global, but performed at a spatial resolution that is much closer to the scale of individual afforestation projects (~5 km^2–25 km^2). It is only conducted on areas where afforestation could take place. These are chosen as areas presently occupied by cropland and that, according to estimates of potential vegetation, would be occupied by forests if it were not for human activities. The assumption is that afforestation is not a viable mitigation strategy if the existence of the forest requires artificial supply of water, nutrients or other type of high intensity management. Another important distinction is that our input is based on observed and not modelled results. The analysis consists of comparing the radiative effects of the carbon drawdown resulting from the increase in land carbon storage to the radiative effects of changes in surface albedo, latent heat flux and cloud cover due to afforestation.

Our analyses provide estimates of the radiative effects of small scale afforestation and were not designed to determine the impacts of afforestation on atmospheric circulation nor the effects of regional or continental land cover change. That is, results should not be integrated into global values and much less, reversed and used as estimates of large scale deforestation (cutting down the Amazon for example). While the sensitivity of results to climate change is discussed, the goal is to provide a best estimate of the effects of afforestation under the present climate. These limitations are imposed by our use of satellite measurements and not model simulations. While some flexibility and the effects of some climate related feed-backs are lost, the adoption of satellite data makes it possible to estimate the albedo effects of afforestation at an unprecedented resolution and, at the same time, avoid uncertainties associated with modeling of snow cover and albedo. The use of satellite land cover in tandem with biome-based land carbon density also provides high resolution estimates of carbon density change.

Our approach generates estimates of the climatic effects of afforestation that take into account the effects of albedo at a resolution pertinent to individual afforestation projects making them a viable tool in carbon policy decision making.

2. Data and methods

Analysis consists of using a present day land cover data set in conjunction with a potential vegetation data set to identify 5×5 km pixels where present day land cover is cropland and where the potential vegetation land cover is forest. Atmospheric carbon drawdown and radiative effects of land cover change are then estimated based on conversion of the entire 5×5 km pixel from cropland to forest. The sections below describe the data and methods used for these estimates. As analyses are only performed on areas where present day cover is cropland and potential vegetation cover is forest, in the text “present day” vegetation is equivalent to cropland and “potential” vegetation is equivalent to forest.

2.1. Potential vegetation

The present day potential vegetation estimates come from the reconstruction by (Ramankutty and Foley, 1999) with five minute spatial resolution and represent the vegetation that would most likely exist in 1992 in the absence of human activities. Prior to analysis these data were interpolated using a nearest neighbor method into a $0.05\times 0.05°$ grid. As albedo is estimated based on relationships between albedo and International Geosphere–Biosphere Program (IGBP) vegetation types, the potential vegetation classes were converted into the IGBP vegetation classes (Belward et al., 1999) (see Table 1 in Appendix A).

2.2. Present day land cover

Present day land cover data are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover product (Friedl et al., 2002). The adopted values are the dominant vegetation in 2001 from the MOD12C1 $0.05\times 0.05°$ global gridded product with IGBP classification as provided by the Land Cover and Land Cover Dynamics group at Boston University (LCD-BU, 2008).

2.3. Snow cover

Snow cover data come from the MODIS MOD10CM global monthly $0.05\times 0.05°$ gridded product as provided by the MODIS Land group (Hall and Riggs, 2007; MLG, 2008). The data are used to generate a monthly climatology of snow cover areal fraction. The MOD10CM data were available for the years of 2000, 2001, 2003 and 2005 but coverage was not continuous. The number of months averaged to produce the climatology ranges from 3 to 4, with the exception of June, with two values.

2.4. Albedo

The albedo values are estimated based on the relationship between vegetation type and snow free albedo obtained by Gao et al. (2005) and the relationship between vegetation type and snow covered albedo presented by Moody et al. (2007). Both of these use the IGBP vegetation classes and both present maximum and minimum albedo values for each class. The land cover–albedo correlation is a function of latitude for the snow free albedo and spatially constant in the snow covered case. Monthly maps of maximum, minimum and average albedo are calculated through a simple weighted average: $\alpha = F\alpha_{vs} + (1-F)\alpha_v$, where α is the total albedo, F is the snow covered fraction, α_v is the snow free albedo, α_{vs} the snow covered albedo and the subscript v indicates the fact that the albedo is a function of the local dominant vegetation type as determined by the potential vegetation or MODIS land cover data.