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Global and Local Effect of Increasing Land Surface Albedo as a Geo-Engineering Adaptation/Mitigation Option: A Study Case of Mediterranean Greenhouse Farming

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1. Introduction

Current warming trends have been generated by a recent imbalance in the Earth's energy budget, characterized by the reduction in 2.6 Wm^{-2} of the global mean annual outgoing terrestrial longwave (LW) radiation from pre-industrial times (Forster et al., 2007). As a result, there is an excess of incoming solar shortwave (SW) radiation that is driving surface and atmospheric temperatures to higher values of equilibrium. This alteration is called radiative forcing (RF) of the climate, and is very probably originated on the unprecedented growth of greenhouse gases (GHGs) in the atmosphere due to human activities.

The reduction to zero emissions might be the only long term effective action to stabilize temperatures at reasonable levels (Mathews & Caldeira, 2008), before impacts are too catastrophic to manage. But on the other hand, in recent years there is a growing interest in the design of geo-engineering strategies to offset this warming exerted by GHGs through radiative rebalancing of the Earth´s energy budget. These proposals can be divided in two groups, according to which parte of the energy budget is addressed for rebalancing. The first group, named as Solar Radiation Management tecniques (SRM), joins up all strategies that attempt to reduce the net amount of SW radiation absorbed by the Earth, by limiting the solar energy reaching the planet. SRM can be achieved by increasing the reflectivity or "albedo" of the Earth to SW radiation at different levels of the atmosphere, at the surface, or even from the outer space. The second group, called Carbon Dioxide Removal (CDR), groups all strategies that aim to increase the amount of LW radiation emitted by the Earth, directly counteracting the greenhouse effect by actively removing the excess CO_2 from the atmosphere, and storing it in long term reservoirs.

One practical way to make comparisons among the potential impacts on climate of different agents is using estimated RF values, thought it must be borne in mind that this metric does not fully represent their overall impact on climate (Pielke et al., 2002), and that further modelling studies are required. Lenton & Vaughan (2009) have recently quantified in terms of RF the climate cooling potential of a wide range of geo-engineering proposals discussed in the recent literature (Boyd, 2008), taking into account their current feasibility of implementation. In the case of proposals aimed to increase the Earth's albedo at low levels, their estimation of RF potentials (SWRF) is summarized in the Table 1:

Option	Fraction of Earth for implementation	Albedo change within area	Planetary albedo change	Global Radiative Forcing (Wm^{-2})
		Increase marine cloud albedo		
Mechanical	0.175	0.074	0.011	−3.71
Biological	0.1	0.008	0.000056	−0.019
		Increase land surface albedo		
Desert	0.02	0.44	0.0064	−2.12
Grassland	0.075	0.0425	0.0015	−0.51
Cropland	0.028	0.08	0.0011	−0.35
Settlements	0.0064	0.15	0.00046	−0.15
Urban	0.0029	0.1	0.00014	-0.047

Table 1. Estimated radiative forcing potential of different SRM geo-engineering proposals (Adapted from Lenton & Vaughan, 2009).

As it can be concluded from these values, most SRM geo-engineering proposals seem to have a limited effectiveness in offsetting present and projected forcing due to GHGs increase. Only "whitening" marine clouds through aerosol seeding, or enhancing albedo on a huge fraction of the Earth's surface through land cover changes, i.e. on big desserts, could achieve levels of forcing high enough as to counteract present unbalance, as well as the estimated forcing due to a doubling of atmospheric CO_2 (+3.71 Wm^{-2}) (Forster et al., 2007). However, these two approaches are still in an early stage of development, and their global scale implementation seems not to be feasible nowadays due to technical and financial barriers related to its big required scale of application.

Nonetheless, though this can be true at a global scale, a different perspective of geo-engineering is usually missed: its value as an effective and cost feasible strategy for local and regional adaptation to projected warming. The increase of land cover albedo at small scales appears nowadays as one of the few available geo-engineering options, particularly to offset or minimize global warming impact over human settlements. The physical basis of this strategy is an SRM approach, reflecting back to the outer space a higher amount of reflected shortwave solar energy than pre-existing land cover over a given area. This way, less energy is available to heat the surface air above when emitted back as sensible heat flux from the surface, thus resulting in a net cooling effect that can totally or partially compensate warming due to GHGs in the area of implementation. At the moment, the most promising strategy of SRM geo-engineering, increasingly being considered by policymakers, is increasing urban albedo through cool roofs and pavements promotion.

2. Cool roofs strategy

In May 2009, the US Secretary of State Steve Chu launched a global call to promote albedo increase in major urban areas in the world. This is one of the first calls from a high level policymaker to promote ge-enginering strategies to counteract global warming. His call was supported by a simulation study carried out by scientists at the Lawrence Berkeley National Laboratory (USA) (Akbari et al., 2008). In this work it was estimated that global implementation of cool roofs in the big metropolitan areas could offset as much as 44 Gt of emitted CO_2, an amount that would counteract the radiative effect of the growth in CO_2-equivalent emission rates for 11 years.

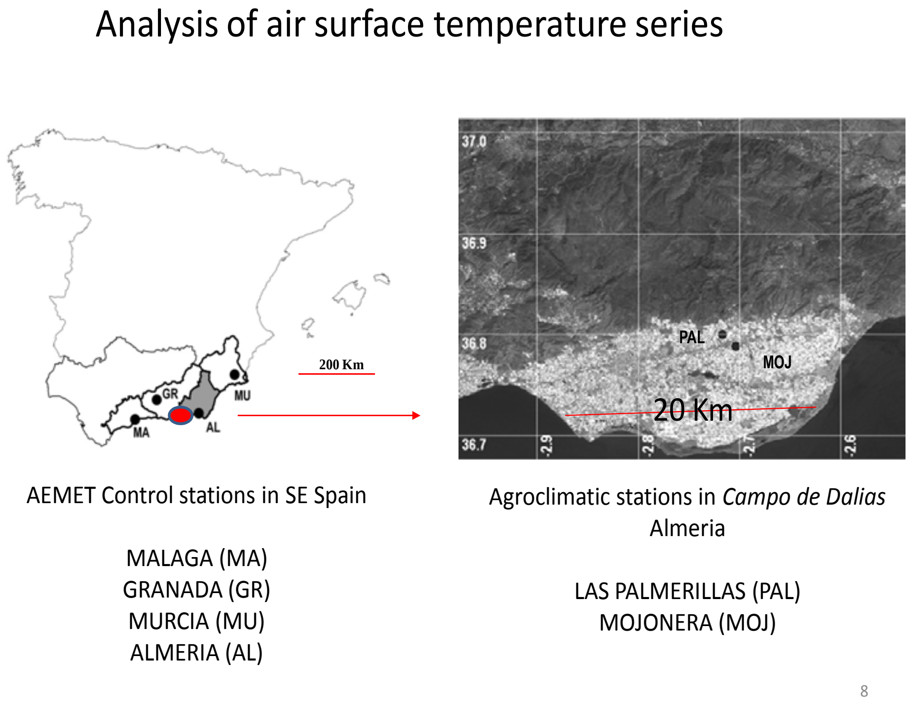
However, an essential parameter to project micro-climate impacts of this geo-engineering strategy not addressed in this study was to determine the local climatic sensitivity associated to a given density and total surface of albedo enhancement. This question needs further radiative transfer modelling validated with empirical study cases. This means that projections of changes in mean temperature and other variables must be linked to independent variables such as extension and distribution of modified surface, time for local climate to adjust to new reflectivity, and changes in RF due to projected increases GHGs emissions. Some global simulations have been published with estimations of temperature changes associated to surface albedo changes (Betts, 2000; Myhre & Myhre, 2003). A further progress in this field is a recent work (Menon et al., 2010) that includes an estimation of the climatic sensitivity of the development of this strategy on global urban areas through a GEOS-5 GCM simulation. In this work they showed the potential effectiveness in reducing high summer temperatures in urban areas, thus mitigating the effects of urban heat islands on energy consumption, pollution, and human health. The potential of cool roofs and pavements for regional adaptation was also reported, with an increase in the total outgoing radiation by 2.3 Wm^{-2} for an average 0.01 increase in surface albedo in the continental US, and land surface temperature decreased by 0.03 K.

Menon et al. (2010) increase substantially the potential forcing that can be achieved by urban albedo enhancement, in comparison to Lenton & Vaughan (2009) estimations. The difference is due to divergences in the estimations of global urban area (1% of global land surface in the first work). Nevertheless, and though the global average increase in the total outgoing radiation was 0.5 W m^{-2} for a simulated 0.1 increase in urban albedo in all global land areas, the global summer temperature reduction obtained by these authors still seems to be negligible (0.008 K), if we take into account that the projections for future warming at the end of this century range from 2-6 ^{o}C, depending on emission trends. However, the reductions obtained in regional and seasonal temperatures are big enough as to consider albedo enhancement as a key adaptation strategy for the next decades, and these global simulations studies highlight the need to study the potential of albedo forcing at smaller scales, i.e. in regional or local domains. A growing number of simulation research with meso-scale models such as Weather Research and Forecasting (WRF, National Center for Atmospheric Research, Boulder, CO, USA) is getting added to literature, but there are still a very few observational studies that show the impact of recent land albedo changes in long term air surface temperature trends. One of these studies (Campra et al., 2008) is summarized in the next section.

3. Albedo enhancement experience by greenhouse farming development in South-eastern Spain

In order to increase the total area of modification of land cover reflectivity, other categories of land use have been proposed to develop this geo-engineering approach, such as pasture and agricultural land, oceans and big desert areas. In the case of farmland, there are several low cost effective strategies that have been proposed to increase reflectivity. The increase in cropland albedo by replacing currently grown crops with high reflective varieties has been recently suggested as a new "bio-geo-engineering" approach (Ridgwell et al., 2009). According to climate simulations made by these authors, the potential for mitigation of regional warming could reach a summertime cooling of >1ºC in mid-latitude arable regions of the northern hemisphere through an albedo increase of 0.04. Same as with urban albedo enhancement, limited impact on global warming was obtained in these simulations.

On the other hand, a particular type of agricultural land cover, greenhouse farming, has shown its efficacy offsetting local warming, showing a net cooling effect in the long term climatic data, as it has been shown in our empiric study in SE Spain (Campra et al., 2008). This recent experience of greenhouses development has resulted in a unique pilot-scale trial, based on field observations of air surface temperatures trends in three decades of a non deliberate geo-engineering experiment based on of the impact of changes in albedo at the biggest concentration of greenhouses in the world (27,000 ha), located at the province of Almeria (Fernandez et al., 2007).



Analysis of air surface temperature series

AEMET Control stations in SE Spain

MALAGA (MA)
GRANADA (GR)
MURCIA (MU)
ALMERIA (AL)

Agroclimatic stations in *Campo de Dalias*
Almeria

LAS PALMERILLAS (PAL)
MOJONERA (MOJ)

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Fig. 1. Location of control (MA, GR, MU, AL) and experimental (PAL, MOJ) stations where air surface temperature series where analyzed in SE Spain (Campra et al., 2008).

Air surface temperature series of agro-climatic stations inside the greenhouses area (MOJ and PAL, Fig 1) showed an anomalous long term cooling trend of -0.3 ºC/decade from 1983 to 2005, during the years of greenhouses expansion, while the control stations located around the area, where no influence from greenhouses land cover is assumed to occur, showed a regional warming trend of +0.4 ºC/decade, that matches with generalized warming in the western Mediterranean area in the same period (Fig. 2).

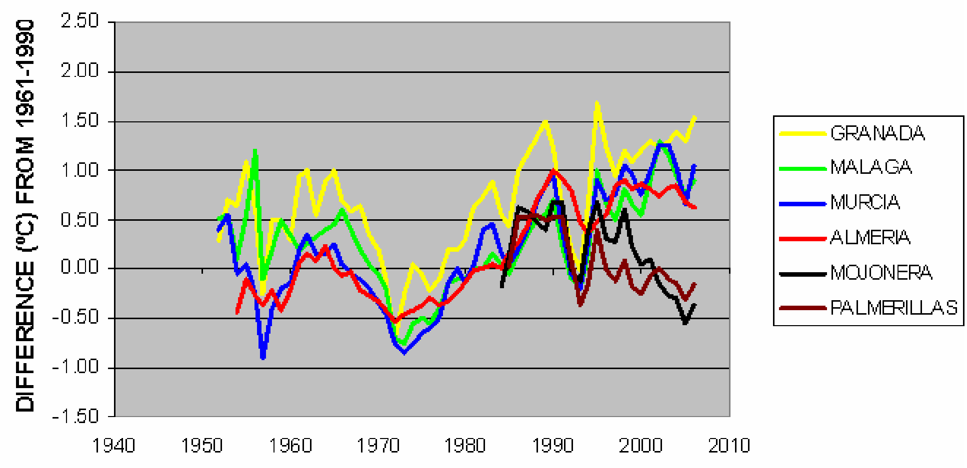

Fig. 2. Anomalies in air surface temperature series in SE Spain (Campra et al., 2008).

The working hypothesis of this study was that this differential climatic trend was caused by the gradual expansion of a highly reflective land cover of plastic greenhouses over a broad area. The increase of surface albedo reduces the net solar SW energy absorbed in the area, and this change in the energy budget might have been the most probable cause of the cooling trend detected in the agro-climatic stations in the area. In order to test this hypothesis, remote sensing albedo data from MODIS were analyzed to compare outgoing SW fluxes (OSW) from greenhouses area, and previous land cover type of semi-arid pastures. The difference series between the two outgoing fluxes is a measure of the SWRF due to land cover change (Fig. 3).

Our ongoing research using meso-scale simulations with WRF (unpublished results) shows changes in the energy budget according with the working hypothesis. The reduction in the sensible heat flux (HFX), and the net SW radiation (netSWrad) are solid evidences of the existence of a causal relationship between albedo change and the decrease in surface air temperatures (Fig 4).

The greenhouses development experience is a solid empiric proof that through designed SRM geo-engineering strategies such as the albedo effect, "cool islands" can be generated to protect human settlements by a low-cost and low-impact effective approach, helping to protect human health, lives and food production from global warming and increased frequency of heat waves projected for the next decades.

Our study shows that the main direct benefit of high albedo surfaces is the potential for adaptation to climate change at local scales, offsetting global warming through the generation of local microclimates in high vulnerability human settlements. This local effect is the key finding of our study in the province of Almeria, but is generally forgotten or just assumed to be a "secondary indirect benefit" of a global CO_2 offsetting. Geo-engineering aimed at increasing albedo at local or meso-scale is not even considered as a mitigation or adaptation measure in international protocols, or IPCC-UN reports. In fact, this strategy can help closing the loop between adaptation and mitigation, an unresolved issue in climate mitigation policies (Parry, 2009).

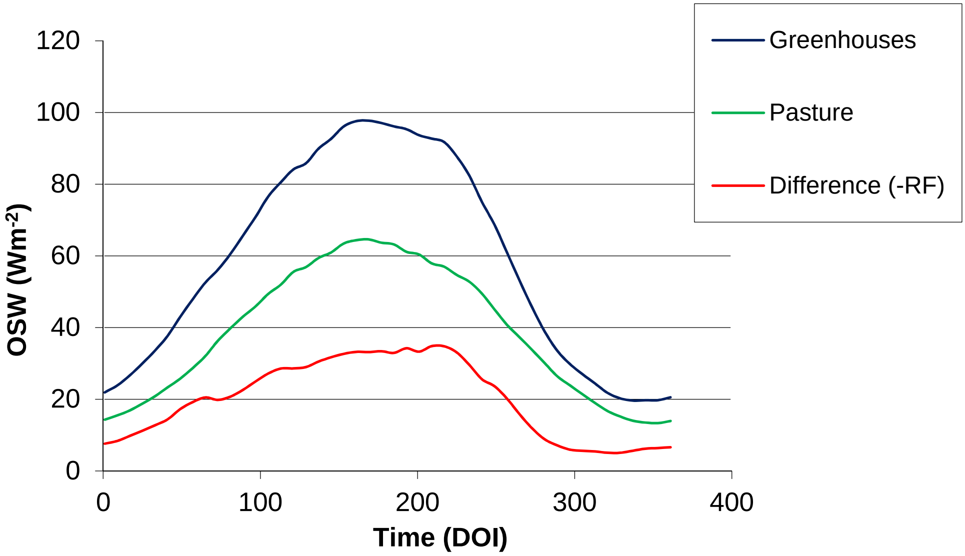

Fig. 3. Annual time series of outgoing solar radiation (OSW) from greenhouses and pasture surface and radiative forcing (-RF) as difference series (Campra et al., 2008).

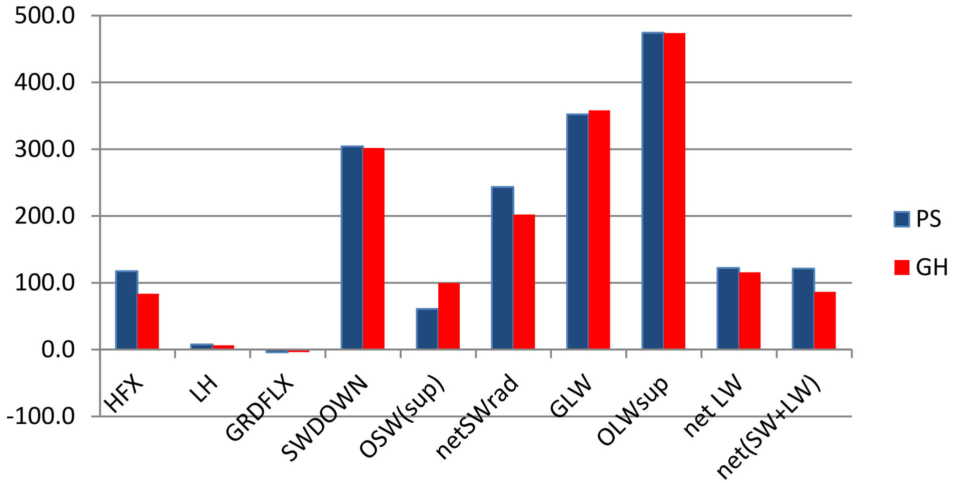

Fig. 4. Change in the surface energy budget components from pasture land use (PS) towards greenhouses land use (GH) (in Wm^{-2}). WRF simulation output: monthly averages for August 2005 (data not published). Radiation components: HFX=sensible heat, LH=latent heat, GRDFLX=ground flux, SWDOWN=incoming solar rad., OSW=outgoing solar rad., netWSrad=net incoming solar rad., GLW=incoming long wave rad., OLW_{sup}=outgoing long wave rad., netLW=net long wave rad., net (SW+LW)=total net rad.

Nonetheless, modelling of the greenhouses land cover change case has not yet been completed as to try to extrapolate the particular outcomes to other areas in the world with a scientifically sound basis. The case of Mediterranean greenhouses development is a very singular experience of climatic geo-engineering whose conclusions by now only apply to a particular set of modified variables affecting a particular local climate. In this sense our ongoing research aims at developing an operative methodology through building a meso-scale WRF model of this particular case, constrained by field climatic observations and remote sensing data of land cover changes that might be adaptable to make projections in different locations in the world.

4. Integration of albedo forcing and carbon footprint of greenhouses production

In our previous research (Campra et al., 2008), we only addressed the impact on the local climate of a change in land cover. However, the net impact on global climate of any geo-engineering option must also be assessed, and three steps are required in the case of surface albedo enhancement strategies:

1. Estimate carbon footprint of the development and maintenance of high albedo surfaces, and compare it to the footprint associated to the economic activities over pre-existing land cover
2. Integrate the global forcing of SW budget change and the forcing exerted by the change in the net GHGs emissions associated to the land use change.
3. Develop meso-scale climate models of the area of implementation of albedo change, in order to simulate the projected change in temperatures in the area of study and in boundary domains around it, up to global scale.

Process	GWP-20	GWP-100	GWP-500
Change in biomass carbon stock	2	2	2
Carbon fixation by crop	-190	-190	-190
Greenhouse infrastructure	283	226	204
Soil preparation	6	6	6
Greenhouse maintenance	<1	<1	<1
Fertilizers	94	93	65
N_2O emissions	55	57	29
Greenhouse disposal	6	3	2
Water pumping	24	22	21
Green waste treatment	83	84	83
Overall emissions (a)	365	303	223
Change in surface albedo (b)	-93	-134	-202
Net with albedo change (c=a+b)	272	168	21
Ratio (c) to (a) (%)	75	56	9

Table 2. Global warming potentials (GWP, in kilograms of CO_2-eq.) at 20, 100 and 500 years associated to the production of 1,000 kg of tomatoes under Mediterranean greenhouses in SE Spain (From Muñoz et al., 2010).

For the case of greenhouse farming, we have estimated the carbon footprint of a representative production by the rigorous methodology of Life Cycle Assessment (LCA) (Muñoz et al., 2010). A cradle-to-gate LCA of an intensive production in the province of

Almeria was first time carried out in this study. First, an inventory of all inputs to the farm was collected. As background emissions data, the Ecoinvent 2.0 database was used (Swiss Centre for Life Cycle Inventories, 2008). This analysis concluded that a gross Global Warming Potential (GWP-100) of 303 kg CO_2-eq. per ton tomato was generated this greenhouse product system (Table 2).

The second step was to develop a novel methodology to integrate SW local radiative forcing and LW global forcing exerted by the indirect GHGs emissions associated to the farming activities, measured as GWPs. Our approach was to consider albedo increase equivalent to "negative emissions" or "emission offset", as this physical change exerts a negative radiative forcing on the climate system opposed to the positive forcing generated by the increase in GHGs. The calculation of CO_2-eq. emissions related to surface albedo change was done with the next three main equations:

1. SW radiative forcing (RF_{TOA}) of a surface albedo change at the top-of-atmosphere (TOA)

$$RF_{TOA} = -R_{TOA}\,\Delta\alpha_{p}, \tag{1}$$

$$\text{where} \quad RF_{TOA} = -R_{S}\,T_{a}\,\Delta\alpha_{s}$$

(R_S= solar radiation at surface ; R_{TOA} = solar radiation at the top of atmosphere; α_p = planetary albedo; α_s = surface albedo; T_a = atmospheric transmittance)

2. CO_2-eq emissions of SW radiative forcing

$$CO_2 - eq. = \frac{A\,\mathrm{RF}_{\mathrm{TOA}}\,\ln 2\;2\mathrm{pCo}_{2,\mathrm{ref}}M_{CO_2}\;m_{air}}{A_{Earth}\Delta F_{2X}\,M_{air}\,AF} \tag{2}$$

where *A* is the area affected by the change in surface albedo (m^2), RF_{TOA} is the SW radiative forcing of a surface albedo change (W m^2) , $pCO_{2,ref}$ is a reference partial CO_2 pressure in the atmosphere (383 ppmv), M_{CO2} is the molecular weight of CO_2 (44.01 g mol^{-1}), m_{air} is 5.148×1015 Mg, A_{Earth} is the area of the Earth (5.1×1014 m^2), ΔF_{2X} is the radiative forcing resulting from a doubling of current CO_2 concentration in the atmosphere (+3.7 W m^{-2}), M_{air} is the molecular weight of dry air (28.95 g mol^{-1}), and AF is the average CO_2 airborne fraction.

3. CO_2-eq emissions avoided through land use change, per functional unit (one kg of fresh product)

$$CO_2 - eq. = \frac{\mathrm{LT}_{\mathrm{FU}}\,R_s\,T_a\Delta\alpha_s}{\mathrm{RF}_{CO_2}\;\mathrm{AF}} \tag{3}$$

Where (LT_{FU}) = land transformation per functional unit (m^2)

As it will be explained in detail in the next section, one of the main sources of uncertainty in these calculations is the calculated value of AF, i.e. the fraction of CO_2 that remains in the atmosphere after carbon cycle has partially removed it in a given time frame. In this study we used a value of 0.48, calculated from the integration of Bern carbon cycle model in a time horizon of 100 years, considering a GWP-100.

Including in the LCA the CO_2-eq emissions equivalence of land cover changes is not a simple task, as many methodological and conceptual problems arise. For instance, the choice of time horizon in the GWP affects the impact of the albedo effect, increasing with time horizon selected. Another source of variability in this methodology is the choice of service lifetime for the activity (here we assumed and expected 50 years lifetime for greenhouse production) (Muñoz et al., 2010). The emission offset increases for shorter lifetimes, for example in this case it increased from 134 to 269 kg CO_2-eq. per ton product when a 25-year lifetime was considered but decreased to 67 kg CO_2-eq. per ton tomato when it was expanded to 100 years.

Through the application of this methodology, the gross GWP-100 estimated (303 kg CO_2-eq. per ton) was reduced to a net 168 kg CO_2-eq. per ton tomato if the change in surface albedo was taken into account. We concluded that the local radiative forcing caused by albedo increase has a remarkable offset effect on the overall GHGs emissions balance of this particular product system, equivalent to 44% of its gross indirect emissions when GWP-100 was considered. However it must be taken into account that albedo effect is always reversible: if in the same system albedo is changed but returned to its previous state at the end of the service lifetime, the net albedo change, and thus, the CO_2-eq. emissions offset, will be zero.

Another particular case where albedo could have an important influence in the CO_2-eq. emission balance is in the context of forestry or any other system involving sharp changes in land cover reflectivity. In this sense, it must be taken into account that forestry plans aimed to mitigate global warming by carbon fixation in biomass should have a complementary assessment of the equivalent forcing exerted by the change in land cover reflectivity. In some regions, particularly in high latitudes where snow cover remains in winter months, this forcing could offset the climatic benefits of carbon fixation (Betts, 2000). This might also happen in semi-arid environments, where the previous disperse shrubland albedo is generally much higher than the forested land albedo.

In any case, other climatic effects apart from temperature changes might be worth to consider, as well as other "conventional" environmental benefits of forestry plans should be regarded as a whole. For example, deforestation in the tropics decreases evapotranspiration rates and increases sensible heat fluxes, resulting in regionally decreased precipitation and increased surface temperature (Bala et al. 2007). In conclusion, new metrics different from radiative forcing and carbon offset might be advisable to take into account these kind of effects of land use change on climate (Pielke et al., 2002). In the words of Dr. R.A. Pielke, "*a more complete indication of human contributions to climate change will require the climatic influences of land-surface conditions and other processes to be factored into climate-change-mitigation strategies. Many of these processes will have strong regional effects that are not represented in a globally averaged metric*." In conclusion, our study is just a first operative approach to highlight the methodological problems that arise when an integration of land albedo changes with associated GHGs emissions is required prior to the development of climate policy regulations related to land use changes.

5. Estimation of carbon offset equivalences of global albedo enhancement

A key conflicting issue introduced by Akbari et al, 2008 is the conversion of SW radiative forcing (SWRF) generated by land cover changes to equivalent CO_2 emissions offset. In this paper, it was estimated that a carbon emissions offset of 44 Gt CO_2 could be achieved by albedo enhancement of main global urban areas. Menon et al. (2010) used the same conversion factors and raised this figure to 57 Gt CO_2 using a summer General Circulation Model (GCM) simulation. These two works are a landmark approach for the estimation of global GHGs offset by albedo increase at urban areas, and offer a remarkable scientific basis for the development of more inclusive climate protocols in the post-Kyoto agreements that do not just rely on GHGs emissions reductions as the only mitigation currency. However, these global estimates should be carefully revised when local or regional effects are to be considered. Furthermore, as we have shown before, there are still complex methodological issues when we pretend to express SWRF due to albedo changes in terms of equivalent reduction in carbon emissions. There are at least 3 main sources of uncertainty that must carefully be taken into account:

1. The calculation of SWRF exerted per unit albedo change, and the use of global or regional averages of this parameter in the estimation of carbon offsets at particular cases
2. The equivalence parameter between SWRF per unit albedo change and the amount of atmospheric carbon that would exert the same but opposite forcing
3. The conversion from that atmospheric carbon to equivalent carbon emissions reduction

5.1 SWRF per unit albedo change

There are still significant uncertainties in the SWRF generated per unit of albedo increase, both at global and local scales. Radiative forcing associated with land use changes has been derived largely from GCM simulations (Hansen et al. 1997; Betts, 2001), using climate simulations, and there are very few observational estimates of this “missing” radiative forcing (Myhre et al. 2005). Some of these studies have shown that the GCM computations significantly underestimate the local SWRF due to land use changes, with observational estimates even more than twice the model-derived values over some regions (Nair et al., 2007). Finally, an additional factor not to be forgotten is that Earth radiation budget changes with time, making more confusing to determine the best value from literature.

In the case of observational studies, such as our work in Almeria greenhouses (Campra et al. 2008), we used and empirical approach and calculated this forcing in our area of study from the outgoing SW radiation (OSR), by the formula from Betts (2001):

$$\mathrm{SWRF} = \mathrm{OSR}_{\text{final land cover}} - \mathrm{OSR}_{\text{fprior land cover}} \tag{4}$$

OSR values were calculated from averaged satellite MODIS data, and SW incoming radiation using an insolation model that accounted for local geographic factors and transmissivity in clear sky conditions (Van Dam, 2000). By this method we calculated an annual averaged SWRF of -19.8 W m^{-2} associated to an average increase albedo of 0.09 in the study area. From these data we can obtain an observational estimate of -2.2 W m^{-2} of SWRF for every 0.01 albedo increase. This forcing is almost double than the forcing of -1.27 W m-2 estimated by Akbari et al. (2008) at global scale. Hansen et al. (1997) did not provide any direct estimate of SWRF associated to a global albedo increase. Instead they used a global climate model with an idealized global geography, and determined the effectiveness of surface albedo forcing applied on fictitious land masses. As they state, this approach was intended to analyze climatic mechanisms, rather than to simulate impacts on specific real world regions. On the contrary, Hatzianastassiou et al (2004), used a radiative transfer model coupled with climatological data to estimate Earth SW radiation budget at top of atmosphere (TOA), and performed sensitivity tests of their model to changes in relevant parameters such as albedo, reporting a 3.3 W m^{-2} change in OSR at TOA with a simulated 10% increase in surface planetary albedo. If we combine this sensitivity of SW radiation budget at TOA with the estimation of surface albedo of 0.129 given by these authors with the same model (Hatzianastassiou et al, 2005), a 0.01 increase of surface albedo equals to a global SWRF of -2.57 W m^{-2} at TOA, again far from Akbari et al. (2008) lower estimate.

It is important to notice that surface albedo changes do not produce equivalent changes in planetary albedo, and must be adjusted by atmospheric absorption and reflection. Thus, when comparing forcings of GHGs TOA, and SWRF due to land use change, both estimates must refer to the net radiative flux change at the same level in the atmosphere, and for the same state of adjustment of the stratospheric temperature profile (Hansen et al., 1997). In this sense, as radiative forcing estimates of GHGs generally refer to values at TOA (Hansen et al., 1997, Myhre et al., 1998), so radiative forcing due to albedo increase must be estimated at TOA as well for comparison. However, adjustment of stratospheric temperatures is not so relevant when dealing with SWRF.

Therefore, the value of estimated global SWRF per 0.01 albedo increase of -1.27 W m^{-2} used in Akbari et al. (2008) needs further discussion, as all CO_2 offset potential calculations are drastically affected by this estimation. For the calculation of this key parameter, they use an averaged value (1984-2000) of total incoming SW Radiation (SWDOWN) at surface of 172 Wm^{-2}, obtained from Hatzianastassiou et al. (2005). This value is at the lower end of previous estimates reviewed by these authors (169-219 Wm^{-2}). Similarly, the value of net SWDOWN at surface (total minus reflected) given by these authors (149 Wm^{-2}), is at the lower range of earth energy budget estimates reviewed (142-191 Wm^{-2}). These values are significantly smaller than most previous estimates, by up to 30 Wm^{-2}, and disagreement is associated with differences in atmospheric absorption. However, Earth radiation budgets at surface and TOA from Hatzianastassiou et al. (2005, 2004) seems very reliable, as they have been validated against surface measurements with good agreement with the model.

Another source of uncertainty of Akbari et al. (2008) estimate is that it is based on the combination of simulated data from two different modelling studies, (Kiehl and Trenberth, 1997, and Hatzianastassiou et al. 2005), thus resulting in a lack of methodological coherence. There is a remarkable difference in net SWDOWN radiation between both estimates, that arises from an overestimation of absorbed SW radiation by atmosphere in the last study (26.7%), compared to earlier studies (20%). However, when calculating *f* (fraction of radiation absorbed by the atmosphere), Akbari et al. (2008) use a SWDOWN value of 172 Wm^{-2} from Hatzianastassiou et al. 2005, and then simply scale down data from (Kiehl and Trenberth, 1997), considering the value of 30 Wm^{-2} as the OSW radiation AT SURFACE. However, this value is referred in the modelling as the OSW radiation AT THE TOA (although the "30" label in Figure 7 can mislead). It makes no sense to reduce its magnitude by atmospheric correction (*f*) as Kiehl and Trenberth have already accounted for any further absorption in their 67 Wm^{-2} value of total SW absorbed radiation in atmosphere.

In order to make this key issue clearer, we can better use a simple analytical approach recently employed to evaluate the radiative forcing potential of different geo-engineering options (Lenton & Vaughan, 2009). Forcing at TOA caused by planetary albedo change $\Delta\alpha_p$ can be estimated from average incoming solar radiation at TOA (DSR), by the formula:

$$SWRF_{TOA} = DSR_{TOA}\,\Delta\alpha_p \tag{5}$$

But planetary albedo has two components, atmospheric albedo (α_a), and surface albedo (α_s), and the latter must be corrected at TOA with atmospheric absorption (A_a) and atmospheric albedo (α_a). This way, forcing due to land albedo increase (SWRF) can be calculated as:

$$SWRF = DSR_{TOA} [\Delta\alpha_s (1- \alpha_a) (1- A_a)] \quad (6)$$

Lenton & Vaughan (2009) make a global estimation of forcing using global energy budget values (α_a, A_a, and net DSR_{TOA}) taken from Kiehl and Trenberth (1997) to obtain an $SWRF_{TOA} = DSR_{TOA}\ 0.579\ \Delta\alpha_s$. Through this formula we can obtain a parameter of SWRF for every 0.01 increase in surface albedo equal to -1.98 W m^{-2}. This is the constant parameter value these authors use to assess the potential for all geo-engineering options based on surface albedo increase.

However, if alternatively we use global energy budget values from Hatzianastassiou et al. (2005), then

$$SWRF_{TOA} = DSR_{TOA}\ 0.50\ \Delta\alpha_s \quad (7)$$

and SWRF for every 0.01 increase in surface albedo results in -1.71 W m^{-2}, still well above Akbari et al. (2008) estimate (+34%).

These conflicting issues have been exposed above to highlight that forcing per unit to albedo increase is a key parameter that needs a more detailed analysis and validation against local surface measurements, as the final associated carbon offset is directly biased by the value of choice.

As an example, in Table 3 is summarized the big changes in final annual CO_2 offset potential of urban albedo increase at urban areas in the state of California, implemented in a 15 year period, depending on the value used in different works for this parameter.

	Akbari et al., 2008	Hatzianastassiou et al., 2005	Lenton & Vaughan, 2009	Lenton & Vaughan, 2009	Campra et al., 2008
Data source[1]	Ref.	RAD	ERB1	ERB2	AL
SWRF per +0.01 albedo (W m-2)	-1.27	-2.57	-1.98	-1.71	-2.2
California Urban offset ($MTCO_2$-eq/year)	31	63	48	42	54

[1] Data used for estimations: Ref.= from Kiehl and Trenberth, 1997, and Hatzianastassiou et al. 2005; RAD= From radiative transfer model; ERB1= based on radiation budget from Kiehl and Trenberth, 1997; ERB2= based on radiation budget from Hatzianastassiou et al., 2005; AL= empiric value for Almeria study case, from MODIS OSW data (lat N 36° 45')

Table 3. Forcing per unit albedo change and estimation of associated carbon emissions offset in California urban areas, according to the values of this parameter in different works

Finally, it must be taken into account that energy radiation budget of the Earth changes with time, and this is affecting the value of this key parameter. For instance, Hatzianastassiou et al. (2005) detected a decadal increase in solar absorption of 2.2 Wm^{-2}, over the period 1984-2000, probably due to reduction of low level clouds.

On the other hand, a linear relation between global albedo increase and SWRF cannot be directly applied to local or regional cases, whatever the value of the equivalence parameter used. The uncertainties and the geographic variation of the equivalence between albedo increase and SWRF are too big as to simply assume an averaged value of -1.27 W m^{-2} , for any location in the world. Due to variability of latitude and average cloud cover, there will be significantly different values of this parameter than any global average estimate, resulting in an underestimation or over estimations of CO_2 offset potentials of albedo increase.

Ultimately, given the uncertainties in global estimates, in practice the issue of applicating global studies to particular urban areas could be overcome by the use of updated local surface based observational estimates of radiative fluxes, averaging long term climatic data. The effectiveness of the changes in surface albedo is a function of the geographic location of the changes. Estimation of this key parameter must include the time-space variability in net incoming solar radiation fields. Local observational estimates of average SWDOWN and OSR at surface are needed. This estimates must integrate different factors, mainly latitude and average cloud cover, but also key variables in urban areas such as aerosol pollution. Updated surface radiation data sets can be used to determine the annual average of net radiation. Alternatively, SWRF can be calculated from OSR data at TOA obtained from remote sensing products, but resolution of these products might do more practical the use of surface observations when dealing with urban albedo changes.

5.2 The equivalence parameter between SWRF per unit albedo change and the amount of atmospheric carbon offset that would exert the same forcing

This issue ultimately deals with the choice of a correct parameter that accounts for the longwave radiative forcing (LWRF) exerted by a unit CO_2-eq or the estimate of adjusted (TOA) radiative forcing per ton CO_2. Akbari et al. (2008) use a RF value of 0.91 kW/tonne of CO_2 for a 385 ppmv concentration, based on estimates by Hansen et al. (2005) and Myhre et al. (1998), who use a RF [Wm^{-2}] = $5.35 \ln(1 + \Delta C/C)$, where ΔC is the difference from pre-industrial times to current CO_2 concentration. The problem is that this parameter can have different values according to the methodological approach, and must also be actualized with present concentration.

5.3 The conversion from atmospheric carbon equivalence to carbon emissions reduction

Given the ultimate goal of computing albedo changes in climate policy, a key issue has arisen when the forcing on climate of a static alteration of the energy budget has to be compared to time-varying forcing exerted by emissions of GHGs. The standard emission metric used in United Nations Framework Convention on Climate Change (UNFCCC) and carbon markets is the GWP (Forster et al., 2007), that was formulated to compare the contribution of different GHGs to climate change over an arbitrary period of time, set in 100 years in the Kyoto Protocol. The calculation of GWPs of different agents involves the integration of their forcing per unit mass increase in a given time horizon, and includes a time-dependent abundance of both the gas considered and the reference gas (CO_2). One of the problems of GWP metrics is that it does not account for the different residence times of different forcing agents. This problem of time varying impacts becomes even more complex when trying to express albedo forcing in terms of GWP. There are two basic conflicting issues here:

1. Whether the use of a correction factor based on CO_2 decay concentration is appropriate or not when comparing to equivalent instantaneous forcing of albedo changes.

As we showed in our approach to the integration of albedo forcing and carbon footprint (Muñoz et al., 2010), this mixing of a static invariant forcing (SWRF) and a time dependent forcing ($LWRF_{CO2}$) that changes with gas concentration is still controversial and methodologically complex, and might be an inappropriate approach.

2. The choice of a given value for the CO_2 airborne fraction (AF). If this correction is applied, the methodological approach chosen to integrate the carbon decay in a given time frame can yield different values of the AF, and marked differences in final carbon offsets.

In one of the pioneering works dealing with the integration of albedo and carbon forcing, Betts (2000) accounts for an AF of emissions of 0.5, assumed to remain constant over forest growth timescales. This figure is used as well by Akabari et al. (2008), and Menon et al. (2010). This value of AF is obtained by a simple arithmetic average of the fraction of fossil fuel emissions remaining in the atmosphere each year for the period 1958-2005 (Denmann, 2007). However, the range of AF in those years is almost (0.3-0.8), and the inter-annual variability is two broad for this fixed value of 0.5 to be considered as an intrinsic property of the climatic system. Furthermore, simulation studies constrained by observations give a similar range of uncertainty in the value of AF, and future projections yield lower AF as CO_2 concentration increases in the atmosphere (Fig. 5).

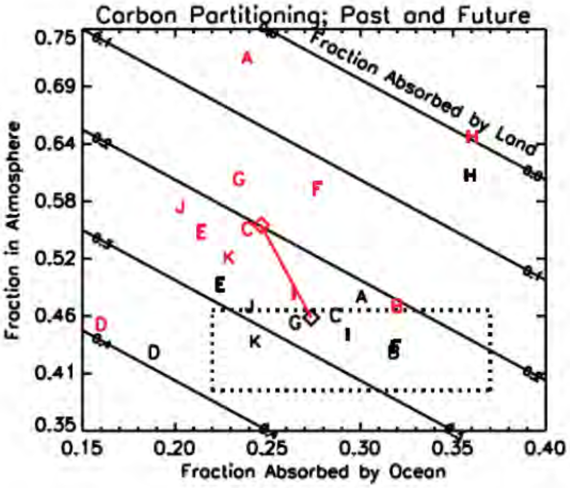

Fig. 5. Predicted increase in the fraction of total emissions that add to atmospheric CO_2. Changes in the mean partitioning of emissions as simulated by the C4MIP models up to 2000 (black symbols) and for the entire simulation period to 2100 (red symbols). The box shown by the dotted line is a constraint on the historical carbon balance based on records of atmospheric CO_2 increase. The black and red diamonds show the model-mean carbon partitioning for the historical period and the entire simulation period, respectively. (From Denmann et al., 2007).

As it can be seen, the choice of an AF of 0.5 seems too simplistic, and other proposals address this issue by introducing correction operations based on atmospheric carbon decay models. For instance, in our work on greenhouses footprint (Muñoz et al, 2010) we used an simple integration of the Bern carbon cycle model (Joos et al, 1996) in a time horizon of 100 years, generally used in the calculation of GWP, to obtain an AF value of 0.48. According to this model, after 10 years 66% of the initial emission remains in the atmosphere, while only 36% remains after 100 years. As a consequence, the choice of a time horizon affects the magnitude of the CO2-eq.emissions. In a more complex formulation, Schwaiger & Bird (2010) use a convolution operation to integrate the instantaneous forcing by albedo change and the inverse of a carbon decay function.

In conclusion, the conversion of albedo forcing into emissions equivalent is still an open and challenging issue that needs further considerations and consensus prior to the development of accounting standards that provide a tool to implement albedo enhancement policies. It must be bear in mind that, if AF no correction is applied, the value of carbon offset estimations will be at least two fold lower than values corrected with AF.

6. Intensive use of land and high yield conservation

By now, in our estimation of the climatic impact of greenhouse farming development we have accounted for on-site impact of changes in the solar energy budget, and for the global impact related to indirect GHGs emissions required for all inputs and processes in the farm. But there is another remarkable indirect trade-off of this land use transformation that must be accounted for, if we wish to have an overall picture of the climatic and environmental effects on the whole territory of the influence of this productive system. When dealing with changes in the use of land and natural resources by a given human population, not only land use changes, but also associated local population migrations, and changes in the intensity of land use in a broader area of their historical settlement should also be included in the analysis. This way, in the southern Mediterranean coast of Spain, the shift from extensive dry crops towards irrigated intensive greenhouse farming has generated the concentration of highly profitable farming activities in a limited portion of the settling territory of the population, while low income extensive farming and grazing activities have been abandoned in an area around ten times larger. This has boosted a spontaneous recovery of natural vegetation, and allowed the development of forestry plans in the abandoned farmland, with the natural or aided generation of huge carbon sinks in soils and biomass. This sinks should be accounted for when estimating the net environmental and climatic impact of greenhouse farming, urbanization processes or any intensification of land use along with similar changes in the human use of the surrounding territory.

As an example, I will summarize the basic figures of this non intentional trade-off, restricted to the province of Almeria for practical statistical reasons. However, it is difficult to determine the geographical limits of the surrounding area of influence affected by greenhouse farming development. The sudden generation of this new source of income has mostly attracted populations from inland mountains of the province of Almeria, but also from neighbouring province of Granada, and furthermore, an intense migration flow of labourers from 200 different countries around the globe seeking for alternatives to the use of their own homeland.

The province of Almeria has a total extension of 877,400 ha. The population has grown from 357,000 in 1957 to 667,600 in 2008. The Gross Value Added (GVA) of the agricultural sector in this province has multiplied 10 times the value in 1957, and 3 times since the beginning of the greenhouses boom in the early 80s, turning from the poorest provinces in Spain to one of the biggest agricultural exports area in the Mediterranean. At the same time, it has turned from a source of emigrants to an attracting pole of migrants from all over the world.

Despite this economic boom and population growth, the extension of natural areas has not decreased in the province in the last decades (Fig. 6). Greenhouse farming has been concentrated in coastal flat lands accounting for 27,000 ha, just a 3% of the total land in the province. On the contrary, hundreds of thousands of hectares of dry crops and semi-arid pastures (40-50% of total surface of the province) have been abandoned inland, and natural Mediterranean plant communities have since then developed a dynamic process of succession that has transformed thousands of hectares to new shrublands with a potential forestry use. Most abandoned crops do not show in the statistic summary in Fig 5, as they are still accounted in official statistics as farmland, and a big portion of pastures that have also been abandoned are included in the natural areas category. In addition, to this spontaneous recovery, Spanish government plans from the 50s, and more recent EU assistance to farm tree planting have increased the forested surface in 90% from 66,000 ha in 1957 to present 130,000. Along with this, historical erosion in this semi-arid territory has been reduced by the abandonment of extensive areas of mountain dry crops that suffered vegetation clearance and tillage in high steep slopes.

This pattern of land use change in the province (Fig. 6) has been boosted in great part by the new source of income generated by off-season greenhouse production, an activity that has grown thanks to the conjunction of a very specific climatic and export marketing condition. Nonetheless, the growth in population, per capita income, along with the reduction in total extension of human use of land, and the increase and recovery of natural areas characterize a pattern of economic development based on the intensification and concentration of land use that can be adapted to different latitudes on the world in order to achieve both local populations needs and natural habitats and cycles maintenance and regeneration.

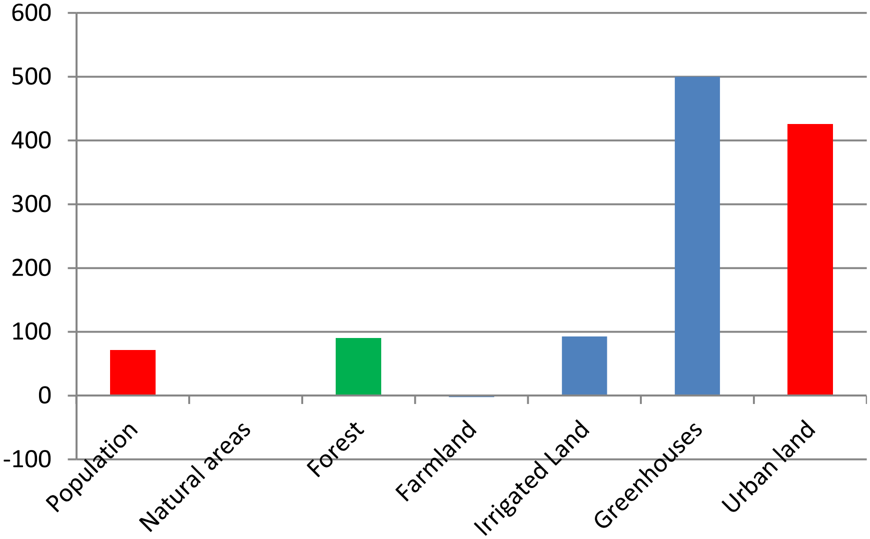

Fig. 6. Rates of change in population and different land use categories in the province of Almeria during the period 1956-2003.

In terms of climate change mitigation, it is important to account for this new carbon sinks generated in this abandoned farmlands. Due to the intense dynamics of this land use changes, the province of Almeria holds one of the most intense carbon sinks in the south of Spain (Agudo, 2007). According to the last regional carbon sink inventory, elaborated according to the IPCC methodology for Land Use and Land Use Change and Forestry (Penmann et al., 2003), the forest areas in the province would be nowadays fixing around 3.8 million tons of CO_2 (Table 4). This figure, only accounting for biomass fixation, should be increased by fixation in soils in regeneration in abandoned farmlands, but this huge sink has not been estimated yet in the area.

	Net carbon fixation in biomass			Province of Almeria
	TCO_2 ha^{-1} stock	surface (ha^{-1})	TCO_2 ha^{-1} a^{-1}	TC ha^{-1} a^{-1}
Forest Land (only trees)	81	154,000	2.5	385,000
Forest Land (shrublands)	120	335,000	10.4	3,490,000
Total				3.87 M TCO_2

Table 4. CO_2 fixation in natural areas in the province of Almeria (from Agudo et al., 2007).

This phenomenon of land use change, associated farmland abandonment, and forests recovery is not unique of greenhouse farming, but is a common trend in many developing areas in the world, such as the northern Mediterranean basin and China (Fig. 8), through natural expansion and afforestation programs.

Global deforestation is mainly due to conversion of forests to agricultural land. However, and though each year about 13 million hectares of the world's forests are lost due to deforestation, the rate of net forest loss is slowing down, thanks to new planting and natural expansion of existing forests due to abandonment of pastures and farmlands. This way, net forest loss dropped from 8.9 million hectares per year in the 90s to 7.3 million hectares per year in the period 2000-2005 (FAO, 2005).

For instance, EU assistance to forestry under the regulation 2080/92, forestry measures on farms, aimed to reduce agricultural surpluses and enhance forest resources, and “combat the greenhouse effect by absorbing carbon dioxide”. In the first period of this plan, one million farmland in EU changed to forestry between 1994 and 1999, a biggest portion in Spain (Evaluation, 2000). Evaluations have shown that this measure has led to the conservation and regeneration of valuable habitats and increases in the use of land for environmental purposes.

It is very important to highlight that this trend goes in the direction of the reversal of historical land use change from pre-industrial reference data of 1750, characterized by a global replacement of forests and natural vegetation by farmland and pastures (Fig. 7). In the last 40 years, 500 million ha have been added to global farmland, 300 out of them are pasture land for extensive livestock grazing. Nowadays, around 40-50% of land surface has an agricultural use, and 80% of deforested land changes towards agricultural or pasture use. Furthermore, present population growth and demands make unsustainable to maintain this trend towards extensive use of land in the present century. Human population is projected to grow from 6,700 million to 9,000 milling around 2050, with skyrocketing demands for meat consumption in developing countries like China and India, due to higher income levels. Is has been estimated that food demands will in crease in 50% in the XXI century. This means increased human use of land, with higher pressure on natural habitats that will additionally suffer intense stress from climatic change. Less adaptation options through migration will be available to natural populations of plants and animals. However, best soils and potential farmland have already been occupied, and further tillage will have to be done in marginal land, with lower quality soils, higher slopes or worst climatic conditions, with lower productivity yields, with growing environmental and sustainability problems.

The only feasible alternative then to make with higher food production compatible with natural habitats conservation and adaptation requirements in a changing climate is the reduction and concentration of human land use through the development of high yield production systems, such as greenhouse horticulture. Additionally, local populations must be offered alternative sources of rent in order to abandon the extensive low income use of land, or they might need to migrate to growing urban areas.

In developed regions such as US and Europe, farmland extension is maintained or decreasing, and forests extension is stabilized or promoted by forestry plans, feasible due to the generation in the last decades of alternative sources of income for rural population, and urbanization processes.

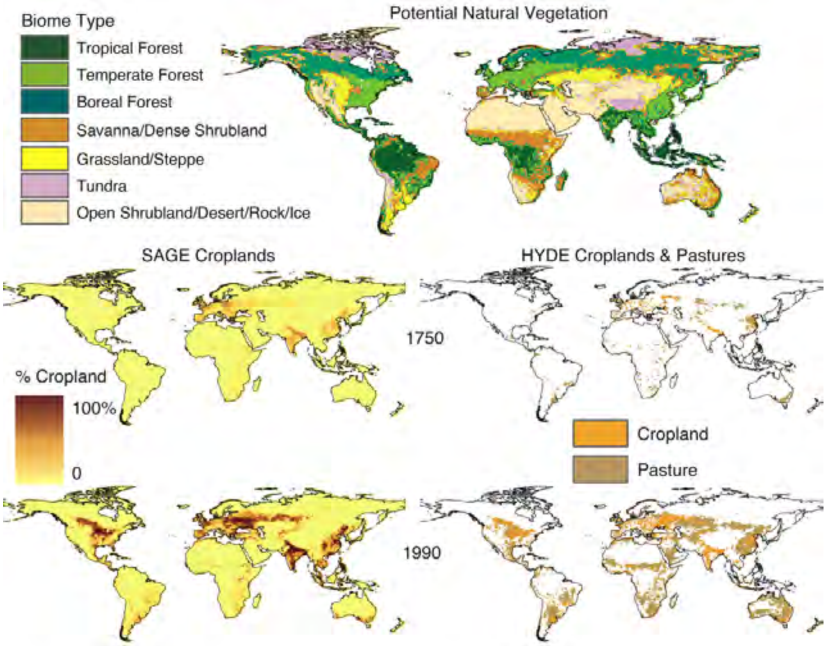

Fig. 7. Potential natural vegetation and land use changes from preindustrial time to present due to agriculture and livestock development (From Forster et al., 2007).

The environmental benefit of this pattern of land use change been named as “high yield conservation”, and the essential message states that “growing more crops per acre leaves more land for Nature”. On the other hand, intensifying food production systems requires higher energy inputs. This issue of energetic supply must be addressed, but is out of the scope of this chapter. This novel approach, that reconciles human land use of the Earth with natural habitats conservation and regeneration and enhancement of natural cycles, is worth to deserve much more consideration by climate and environmental policies, and might become one key option of the human sustainable use of the available surface of the planet in the present century.

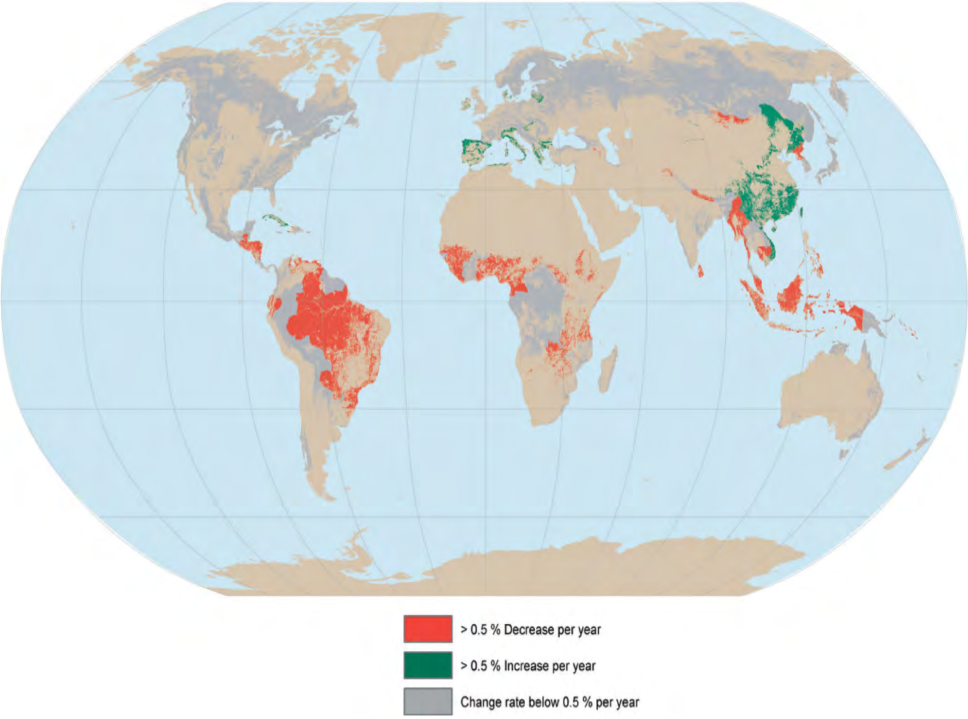

Fig. 8. Recent rates of net forest area change (2000-2005). Red >0.5% decrease per year; Green > 0.5% increase pr year; Grey = change rate below 0.5% per year (FAO, 2005).

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