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Intensification of coffee systems can increase the effectiveness of REDD mechanisms ☆

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ABSTRACT

In agricultural production systems with shade trees, such as coffee, the increase in greenhouse gas (GHG) emissions from production intensification can be compensated for, or even outweighed, by the increase in carbon sequestration into above-ground and below-ground tree biomass. We use data from a long-term coffee agroforestry experiment in Costa Rica to evaluate the trade-offs between intensification, profitability and net greenhouse gas emissions through two scenarios. First, by assessing the GHG emissions associated with conversion from shaded to more profitable full-sun (un-shaded) systems, we calculate the break-even carbon price which would need to be paid to offset the opportunity cost of not converting. The price per tCO_2e of emissions reduction required to compensate for the coffee production revenue foregone varies widely from 9.3 to 196.3 US$ amongst different shaded systems. Second, as an alternative to intensification, production area can be extended onto currently forested land. We estimate this land-use change required to compensate for the shortfall in profitability from retaining lower intensity coffee production systems. For four of the five shade types tested, this land-use change causes additional GHG emissions >5 tCO_2e ha^{-1} yr^{-1} resulting in net emissions >8 tCO_2e ha^{-1} yr^{-1} for the whole system. We conclude that instead, by intensifying production, mechanisms similar to REDD that are based on reducing emissions through avoided land-use change (REAL) could play a major role in increasing the climate change mitigation success of agroforestry systems at the same time as aiding REDD through reducing pressure for further forest conversion to agriculture.

1. Introduction

Agricultural production and land-use change (LUC) together can account for almost one-third of global emissions of greenhouse gases (GHGs) (IPCC, 2007). Climate change mitigation strategies in these areas have therefore become an integral part of sustainable development thinking and planning. Identifying GHG emission hotspots and finding appropriate reduction solutions is, however, not the only challenge: global population has more than doubled in the past 50 years and with it demand for food (FAO, 2011). Historically, food supply and demand have tracked each other (Kendall and Pimentel, 1994) but this is no longer the case with global crop yields increasing at a slower rate than global population growth (Trostle, 2008). The agricultural sector therefore needs to address these multiple needs aiming at the improvement of food security, productivity, climate change mitigation and the sustaining of livelihoods. Projections by the USDA on the development of food prices over the next decades predict no decline in the current high and this could incentivise farmers to convert additional non-crop land, such as secondary (or even primary) forests, into agricultural production (Trostle, 2008). Although increases in food production have raised the average global calorific per capita food supply, the pressures of increased food demand through dietary changes and population growth are rising, especially in low-income countries (FAO, 2011). In turn, pressure on land availability is mounting, leaving forests in tropical regions more vulnerable (IPCC, 2007; Malhi et al., 2008). Recent studies have emphasised the importance of increasing agricultural yields through high intensity production systems, to meet continually increasing global food demand and to reduce carbon (C) loss through LUC (West et al., 2010). Moreover, global emissions from LUC for food production are likely to outweigh those from agricultural intensification, which is estimated to have resulted in a net C emission reduction of 590 $GtCO_2$e globally since 1961 due to avoided land-use conversions (Burney et al., 2010). Many stakeholders, however, consider

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standing forests (especially secondary forests) to be less valuable than alternative land uses and therefore they are under threat of deforestation through land conversion to agriculture (Murdiyarso et al., 2010).

The intricate link between food production and deforestation has been a driver for programmes such as "Reduced Emissions from Deforestation and Forest Degradation" (REDD), where financial mechanisms are used as incentives for not converting forests to other uses. Although individual REDD projects are often seen as a potential source of income (Laurance, 2007; Tollefson, 2008), in their design it will be paramount to assess not only profitability but also the potential for indirect GHG emissions through so-called "leakage". With the arrival of REDD+ programs as an all-encompassing framework under which many global efforts ranging from climate change mitigation to poverty alleviation are now being placed, the debate around trading C for food has gained new momentum. However, concerns about financial viability and competiveness of REDD+ projects (Butler et al., 2009), and their potential to address drivers of deforestation, are being voiced. Their wider success (including aspects of sustainable development, biodiversity conservation and protection of existing forest lands) may depend on intensification of existing agricultural land coupled with explicit policy intervention (Ewers et al., 2009). Activities that address the causes of deforestation, at the same time as presenting a viable financial alternative within existing global markets and the right policy framework, will therefore greatly assist the success of REDD+ programs.

It has been suggested that coffee farming could be considered for qualification under REDD+ activities (Soto-Pinto et al., 2010). Perennial agricultural production systems, especially those including trees such as coffee systems, have the unique potential to sequester and store relatively large amounts of C in above-ground biomass and in soil organic matter (Albrecht and Kandji, 2003; Dossa et al., 2008; Kandji et al., 2006; Mutuo et al., 2005; Segura et al., 2006; Soto-Pinto et al., 2010; Verchot et al., 2007). The C sequestration potential of agroforestry systems has long been documented and is often seen as an attractive option to combine climate change mitigation with adaptation of food production and poverty alleviation (Mutuo et al., 2005). For agroforestry products such as coffee and cocoa, gross C sequestration could even outweigh GHG emissions, making them carbon-neutral or even carbon-negative systems throughout their productive lifetime. Coffee production, however, depends on a combination of regional environmental variables such as temperature, precipitation, altitude and soil properties as well as more system-specific variables such as shade tree species, shade density and management inputs. Indeed, enhancing standing biomass stocks to increase biological C sequestration and thus enable benefit from verified C credits could adversely affect the performance of coffee production systems. Global coffee production has grown by about 50% over the past two decades (www.ico.org, historical data consulted 01.02.13), which has been achieved by either intensification of production, including elimination of shade, or bringing new land into production (Neilson et al., 2012). Lenzen et al. (2012) have demonstrated that the growth in commodities, such as coffee, has contributed to reduction in global biodiversity primarily through habitat loss. Nevertheless, the expansion of coffee has been uneven across the world with some countries' coffee production area contracting (Bosselmann, 2012) and others such as India, Indonesia and Vietnam considerably expanding. During the past two decades coffee production in Indonesia has doubled and in Vietnam has increased 10-fold (Neilson et al., 2012). In both countries this is a major cause of deforestation, contributing to a 17% decline in forest cover in Central Vietnam (D'haeze et al., 2005) and a 50% decline in some parts of Sumatra (Verbist et al., 2005). Thus, mediated through the international coffee market, production deficit of coffee in one country is likely to lead to farmers elsewhere bringing new land into production. Therefore, environmental performance of agriculture (e.g. when changing systems to reduce emissions) should be weighed against a number of other factors such as productivity, profitability and indirect impacts on land-use change.

This study evaluates the trade-off between profitability and climate change mitigation potential through a comparative analysis of a number of coffee production systems within a long-term experiment in Costa Rica, by comparing different agronomic management systems under a range of shade tree types. We further explore how intensification affects the overall C balance and profitability within shaded coffee production systems.

We firstly assess the impact of intensification on the relationship between system productivity and GHG emissions. Secondly, we investigate the extent to which C sequestration into biomass offsets the GHG emissions from agronomic management in determining the difference in overall C balance amongst the systems. We then calculate the price (in foregone revenue from coffee production) of avoiding GHG emissions by retaining existing shaded coffee systems rather than converting to more productive intensive systems, excluding non-market costs and benefits. The final analysis investigates the implications of LUC between forest and agriculture for the net impact of intensification versus extensification of coffee production on GHG emissions. This is done by calculating the LUC emissions associated with extensification, caused by the expansion of less productive coffee systems onto currently non-agricultural, forested land to compensate for the shortfall in profitability due to retaining the lower productivity systems. The net impact of these two components on GHG emissions is calculated. This study hereby aims to inform the debate around the role of agricultural production in climate change mitigation strategies with implications for current C market mechanisms.

2. Methods and materials

2.1. Site description

The research was conducted at a 6-ha field site at Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica (9°53′44″N, 83°40′7″W) at 685 m above sea level, chosen to represent the low altitude coffee growing region.

2.2. Experimental design

The experiment was set up to compare organic and conventional coffee production systems under various types of shade. The main-plot treatments are full sun (FS) and four different individual species (*Erythrina poeppigiana* (E); *Chloroleucon eurycyclum* (C); *Terminalia amazonia* (T)) or combinations (*E. poeppigiana* + *T. amazonia* (ET)) of shade tree. The tree species were selected from those most commonly grown in association with coffee production in the region. The four sub-plot treatments combine different types (conventional and organic) and levels (intensive and moderate) of nutrient and pest management inputs (Table S1). An incomplete factorial design comprising 14 of the potential 20 main-plot/sub-plot treatment combinations was chosen (Table S1), as some combinations are not representative of real farming systems (e.g. FS with organic management). The design is a randomised block with three blocks and one replicate of each treatment per block. A more detailed description of the experiment is reported elsewhere (Noponen et al., 2012). The experiment was monitored for 9 years (2000–2009).

2.3. Carbon footprint

As the aim of this study is to compare GHG emissions from different farming methods, the system boundaries were drawn at the farm gate, including only those emissions directly associated with the production and management of a particular system. At the time of this study, the Publically Available Specification 2050:2011 (PAS 2050), developed by the British Standard Institute, was the only globally recognised, transparent and publically available product carbon footprint (CF) methodology published to-date and was therefore chosen here for all CF calculations. Empirical data were used to calculate biomass and coffee yield for individual production systems; recommended models and emission factors outlined in PAS 2050 were used to estimate all other components of net GHG emissions (BSI, 2011). We recognise the limitations and uncertainties attached to the use of the fixed IPCC tier 1 assumptions about C fluxes, emission factors and models under such standards but consider these acceptable for the purpose of this analysis.

Within PAS 2050, fluxes of the GHGs CO_2, N_2O and CH_4 are accounted for and converted into units of CO_2 equivalents (CO_2e) according to their global warming potential (GWP) over 100 years. Of specific relevance to agricultural CFs are non-CO_2 emissions from livestock, their manure and from soils, which must be included, calculated according to IPCC guidelines for national GHG Inventories (De Klein et al., 2006). Nitrous oxide emissions from soils are accounted for as both direct and indirect emissions resulting from N additions, deposition and leaching. Direct emissions from land use change (LUC) must be included if the land conversion took place on or after the fixed date of the 1st January 1990. As all land in the experiment was in agricultural production prior to 1990, no LUC emissions have been included. Changes in soil C, either as emissions, sequestration or in eroded material, are excluded from PAS 2050 unless they are a direct result of LUC activities. Carbon stored in living organisms such as trees or perennial crops is also excluded from the PAS 2050 method, however for this study, in a separate analysis, the mean annual above-ground C sequestration has been estimated as a separate variable from the CF in order to establish a more complete assessment of the true net C balance of individual treatments (Table S2).

Carbon footprint calculations for each system were based on annualised averages of all inputs and yields since the second year of coffee production, to best represent the whole production system. To allow for a direct comparison between emissions of CO_2e and C sequestration, CF calculations were made on a per-hectare basis. In order to calculate the overall net C balance of systems and to allow for comparison with the GHGs emitted (CF per ha), annual C sequestration in above- and below-ground biomass and litter have been converted into units of CO_2e.

2.4. Estimation of above-ground and below-ground biomass

Above-ground biomass stocks (Table S2) for all treatments were estimated by specific allometric equations which were developed for each shade tree species (Table S3). Below-ground biomass for shade trees was estimated using a function developed by Cairns et al. (1997) and recommended by IPCC (Nabuurs et al., 2003). Above-ground coffee biomass stocks were calculated using an allometric equation developed by Segura et al. (2006) for shaded and un-shaded coffee systems (Table S3). The equations of Dossa et al. (2008) for coffee growing in the open versus under shade were used to estimate coffee bush below-ground biomass (Table S3). Leaf litter and deadwood C stocks were estimated using the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (LULUCF) on measuring and monitoring changes in C stocks (Nabuurs et al., 2003). For all sampled living above-ground biomass and pools such as dead-wood and small-fraction litter, a stock-based approach was adopted in which an annualised average was derived by dividing the results from 2009 by the yceears since establishment of the experiment in 2000 assuming a linear sequestration rate and a start value of zero for all pools.

2.5. Calculation of land-use change emissions

Land-use change emissions and sequestration of CO_2 are consequences of changes in ecosystem C stocks. These emissions and sequestration were calculated using the IPCC guidelines for national GHG Inventories for agriculture, forestry and other land use (De Klein et al., 2006) using inventory data from the experiment. Changes in C stocks for a given land-use category are calculated from fluxes into and out of the above-ground and below-ground biomass, dead-wood and small-fraction litter, and soil organic matter pools. Non-CO_2 GHG emissions derived from sources such as manure, dead-wood, small-fraction litter and soils have also been included using gas- and source-specific emission factors. Although changes in C stocks, for example through LUC, often result in immediate C-balance alteration, IPCC specifies a period of 20 years in which the land remains in the conversion category before a new C-stock equilibrium is expected (De Klein et al., 2006). Therefore, these C-stock changes are annualised for 20 years. Management and shade type for additional LUC area have been assumed to equal that of the tested case in the experiment.

2.6. Cost–benefit analysis

Cost benefit analysis (CBA) was carried out on the individual experimental treatments. All economic data were obtained for Costa Rica on an annual basis to reflect changes in economic conditions, such as price fluctuations with global coffee prices doubling since the establishment of the experiment (International Coffee Organization (ICO), 2011) and fertiliser prices increasing fivefold in the period 2005–2008 (Foresight, 2011). Management and resource inputs were recorded since the onset of the experiment. Actual costs of all inputs for each year since the first year of coffee production (third year after planting) were recorded in their local currency unit (Costa Rican Colon C$, Table S4). The individual treatments were then converted into US$ using an annual mean exchange rate and appraised as their net present values (NPVs). The NPV is expressed as the difference between the discounted present value of past benefits (PV_B) and the discounted present value of past costs (PV_C). Income from firewood and fence-post material has not been taken into account as no accurate data were available for individual treatments. Only the income from the whole experiment was recorded, and this indicates that income from this source is of low economic importance at this stage of timber tree development, contributing less than 1% to the NPV (mean of US$6.14 ha^{-1} yr^{-1}). In addition, the range of other non-market benefits of trees within coffee agroforestry systems were not included as this analysis was intended to focus only on direct farmer income and expenditure.

2.7. Land-use change scenarios

2.7.1. Intensification scenario

Up till the present, the decision-making of most Central American coffee farmers under the past conditions of uncertainty indicates that they have adopted the approach of "maximising the minimum" (maximising return on a limited capacity to invest). The choice of this maximin criterion under uncertainty, even if it led to a lower average outcome, is rational if financial markets are inefficient (for a discussion of this criterion see, e.g., Peterson and Lewis, 1986). A strategy that provides the average gain may be shunned for a strategy that provides a better cushion if things go wrong. The choice of production techniques such as the shaded systems that provide lower average gain in favour of the seemingly more profitable (higher net income per ha) FS systems is observed amongst farms in our study area. Coffee is naturally an understory shrub requiring high nutrient availability to survive the stress of FS conditions; shaded coffee has greater resilience to water and nutrient shortage than under FS (Beer et al., 1997). Although coffee production responds positively to fertilisation at high levels of shade (e.g. over 50%) this response is severely limited by the low light availability. Production response to high fertilisation is greatest in FS conditions. The requirement to maintain high levels of fertilisation in FS systems can cause greater fluctuation in income with changes in fertiliser and coffee prices and constraints on the availability of finance. Nonetheless, some farmers have already made decisions based on "maximising expected value" (maximising net income per ha) and so converted to more profitable high-input FS systems. These have tended to be larger producers better able to access the financial markets. This conversion previously occurred during the 1970s and 1980s when the international coffee agreements supported coffee prices (Goodman, 2008). If global commodity prices remain high, as is foreseen, it will stimulate more farmers to maximise expected value in their decision-making and convert to more profitable high-input systems. The opportunity costs of not converting could be expected to surpass the risk threshold which has stopped farmers converting to high-input FS systems before. However, we do accept that even if this price signal occurs, some farmers will not convert to more profitable systems, the decision making of many will still be dominated by an adversity to risk. Our approach is supported by sensitivity analyses (see results section) based on historical minimum and maximum coffee prices recorded for Costa Rica, and the absolute minimum and maximum values of labour costs recorded for the experiment, during the period 2000–2009. Due to the nature of the input data for materials (the range in value of inputs per ha under each treatment is a combination of different effects, e.g. changes in the level and price of different inputs such as fertiliser or chicken manure) we opted to use the lower and upper 95% confidence interval boundaries of the mean input costs per subplot treatment. Using data of the fluctuation of actual coffee prices, labour costs and input costs over this period, the range of resulting NPV values was calculated on an annual basis for each treatment with all other costs held constant. The opportunity costs of the intensification and extensification scenarios were then calculated for each treatment combination using the mean NPV and the minima and maxima or CI values of NPV.

2.7.2. Extensification scenario

As reviewed above, many coffee farmers in Central America continue to use low-input shaded coffee systems despite their lower yield and potential profitability compared with more intensively managed high-input shade systems. These decisions reflect their response to the uncertainty of future prices of both coffee and expensive agrochemicals, and financial tools to buffer those effects. If farmers decide to retain low levels of agrochemical inputs, rather than converting to a more intensive system, while this may have global benefits of maintaining a lower CF, it also risks reducing the potential contribution of their produce to the national economy and international agricultural markets. Given the strong continuing global demand for coffee, the collective impact of these farmers' decisions is likely to increase pressure to convert additional land to coffee production (an example of "extensification"), in some cases forest land at the agricultural frontier with its associated LUC GHG emissions. Although we know that individual farmers expand or contract the area under coffee in response to market conditions (e.g. Tucker et al., 2010), the major changes in coffee area have been national- and international-level expansions of coffee production bringing new farmers and new land into coffee production. With repeated cycles of expansion and contraction of land area under coffee farming in Central America, there are in many places areas of secondary forest available for reconversion, and at higher altitudes primary forest is being converted where the climate has become relatively more favourable for coffee production (Gay et al., 2006; Guhl, 2008; Tucker, 2008).

2.8. Scenario calculations

To enable both scenario analyses we firstly quantify the overall farm-level GHG emissions (in the form of CF per ha) associated with alternative coffee production systems in the 9-year experiment in Costa Rica. This establishes the order of intensification of the coffee management treatments (applied at the subplot-level) regardless of shade-type (main-plot-treatments). Throughout the text "intensification" refers to higher levels of inputs, resulting in increased coffee production, per unit area and time (Lambin et al., 2001). In the *intensification* scenario, by carrying out a cost–benefit analysis with these historic data, we calculate NPV to identify the most profitable coffee production system (it was FS with conventional intensive management). We then assessed the opportunity costs of avoiding LUC from each shaded system to this intensive system. By calculating the net GHG emissions that would result from these LUC's we determined the break-even price per tonne of avoided CO_2e emissions that would need to be paid to farmers as compensation to offset their opportunity costs of retaining less profitable but lower emission shaded systems (Healey et al., 2000).

Taking the assumption that farming with less productive systems requires a greater land area to produce a given quantity of coffee, we constructed an *extensification* scenario. For this we calculate how much forest land would need to be converted to coffee production under the same management and shade system to generate income sufficient to cover the opportunity cost of maintaining less productive and profitable coffee management systems (within each shade type) rather than intensifying production on the existing coffee farmland. We then assess the contribution of the GHG emissions associated with this LUC to the net impact of retaining a less productive system. The annual CO_2e balance after LUC is calculated by summing the C sequestration into above- and below-ground biomass and litter less the CF on the existing farmed area, less the deforestation LUC emissions and the CF of the additional land area converted from forest (and then farmed with the same management and shade type) (LUC + CF). The results are expressed per land area of existing coffee cultivation. It is assumed that unconverted forest has zero net GHG emissions or C sequestration. For each shade type the scenario tests the net impact on CO_2e balance of retaining each of the less intensive coffee management systems with the required additional land converted to coffee farming as an alternative to converting the existing farmed land to the most profitable (Conventional Intensive (CI) or in two cases where this was excluded, Conventional Moderate (CM)) system within each shade type.

Additional Materials and Methods. For further details on the methods and materials of this study please refer to Supporting Information (SI) Tables and Text.

3. Results

3.1. Effect of system intensification on GHG emissions, C balance and profitability

There is a strong positive correlation between net GHG emissions (CF per ha) and NPV indicating a strong trade-off between GHG emissions' reduction and profitability (Fig. 1). This effect is seen in the comparison of conventional and organic systems and within conventional systems comparing moderate and intensive management inputs: the highest GHG emissions were found in the high-input intensive conventional treatment and the lowest in the moderate-input organic treatment (Fig. 1).

When the annual sequestration of C in biomass and litter is subtracted from the GHG emissions encapsulated in the CF, CO_2e balance varies greatly between shade types (Fig. 2). Systems shaded by the single timber tree species *C. eurycyclum* had significantly ($p < 0.05$) higher (net fixation) C balance ($tCO_2e\ ha^{-1}\ yr^{-1}$) than that of the mixed shade (*E. poeppigiana*/*T. amazonia*), leguminous shade (*E. poeppigiana*) or full sun (FS) systems, and those with the single timber species *T. amazonia* had significantly higher fixation than the later two systems. However, whilst not all trends amongst coffee management systems are consistent across shade types, there was an important interaction. Although, overall, the most intensive coffee management system (CI) produces a significantly higher CF than all others, its C balance (relative to the other systems) is strongly dependent on shade type and tree management, from being the system with the highest positive (sequestration) balance under *T. amazonia* to being the lowest under *E. poeppigiana* (both $p < 0.05$). This difference is mainly due to the dramatically different tree managements applied. *T. amazonia* is left to grow with a minimal pruning regime and responds with increased growth and accumulation of C in biomass when fertilised, while the leguminous shade tree *E. poeppigiana* was completely pruned (pollarded) at about 2 m above ground level, twice a year to allow higher light exposure at times of coffee flowering and maximum input to the soil of N-rich organic matter from the pruning residues (emulating the common practice throughout Costa Rica). No significant differences ($p < 0.05$) were found between Conventional Moderate (CM) and organic intensive (OI) management treatments across shade types except that the former had a more positive C balance under the mixture of *E. poeppigiana* and *T. amazonia*. Taking all of the results together, shade type had a significant ($p < 0.001$) impact on C balance (with a strikingly lower net fixation in the FS than the shaded systems) but the net effect of intensity of coffee management depended on the response of the shade trees to the higher inputs, whether additional C accumulation in biomass out-weighed the increased agronomic emissions (c.f. *T. amazonia*) or not (Fig. 2). Therefore, in these agroforestry systems there is potential for higher emissions from intensification to be offset by greater C sequestration in tree growth.

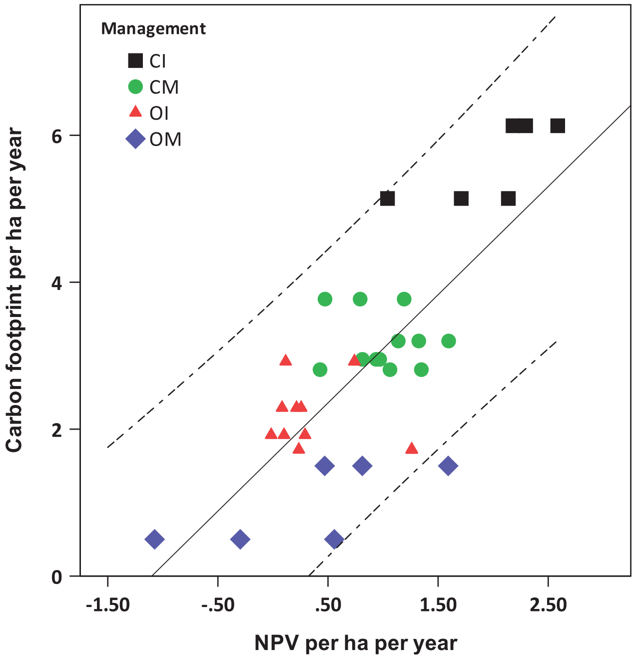

Fig. 1. Relationship between mean CF ($tCO_2e\ ha^{-1}\ yr^{-1}$) and mean NPV (1000 US\$ $ha^{-1}\ yr^{-1}$) for four sub-plot coffee management treatments (conventional intensive (CI) $n = 6$; Conventional Moderate (CM) $n = 12$; organic intensive (OI) $n = 12$; organic moderate (OM) $n = 6$) across four main-plot shade treatments and three replicate blocks in Costa Rica. Fitted line, $r^2 = 0.57$; $CF_{ha} = 1.621 + 1.473 - * NPV$; dashed lines indicate the upper and lower boundaries of the 95% confidence interval values.

3.2. Profitability of different production options

Net present values based on labour, material and other inputs, and coffee production outputs for the years 2003–2009 showed an increase from organic (mean 431 US\$ $ha^{-1}\ yr^{-1}$) to conventional (mean 1425 US\$ $ha^{-1}\ yr^{-1}$) and (in the conventional system) from moderate (mean 1075 US\$ $ha^{-1}\ yr^{-1}$) to intensive (mean 2007 US\$ $ha^{-1}\ yr^{-1}$) input management (Table S5). For the CI management they were also higher under FS than under any shade type by at least an average of 100 US\$ $ha^{-1}\ yr^{-1}$ (Table S5).

3.3. Intensification

The avoided LUC emissions (Table S5) from converting 1 ha of shaded to un-shaded FS system ranged from 5.08 to 25.36 $tCO_2e\ ha^{-1}\ yr^{-1}$ amongst shade types and showed a similar trend amongst shaded systems to their annual sequestration rates (Table 1) with the lowest and highest mean avoided LUC emissions associated with the leguminous tree species *E. poeppigiana* and the timber tree species *C. eurycyclum*, respectively. Similarly, significant differences ($p < 0.05$) were found under *E. poeppigiana* and *T. amazonia* between CI and all other subplot treatments with CI being the lowest under the former and the highest under the latter (a strong interaction with shade type). The break-even C price required to compensate farmers for not intensifying ranged greatly from 9.3 to 196.3 US\$ per sequestered $tCO_2e\ ha^{-1}$ (Table S5) because of the huge variation in profitability (NPV) under the different shade systems. The timber shade species (*T. amazonia* and *C. eurycyclum*), due to their relatively higher sequestration potential, had lower break-even prices on average than leguminous (*E. poeppigiana*) and mixed (*E. poeppigiana*/*T. amazonia*) systems, although no significant differences were found ($p < 0.05$) between the two groups. Break-even C prices were also significantly lower under conventional (mean 42.6 US\$ per sequestered $tCO_2e\ ha^{-1}$) than organic (mean 116.9 US\$ per sequestered $tCO_2e\ ha^{-1}$) management systems ($p < 0.01$).

3.4. Extensification

Without including the effects of extensification through deforestation LUC, all shade-type-coffee-management combination systems demonstrate a positive CO_2e balance (net sequestration) except for the most intensive FS CI system, in which the net CF just outweighed sequestration into biomass and litter (Table 1). However, by including emissions from the deforestation LUC needed to provide the additional farmed area required to bring each less-intensive system up to the NPV of the most intensive management under that shade system, only the two coffee management systems under the *T. amazonia* shade type remained positive in their CO_2e balance. For all the other six combinations of shade type and management system, the emissions caused by the forest conversion LUC outweigh the sequestration in the existing and additional farmed area by at least 1.8 times, resulting in an overall net negative CO_2e balance (net emissions), up to 102 $tCO_2e\ ha^{-1}\ yr^{-1}$ for the OI system under *C. eurycyclum* shade.

3.5. Sensitivity of the intensification and extensification scenarios to coffee prices, labour and input costs

Analysis of the sensitivity of NPV for different production systems to coffee prices shows that with maximum prices

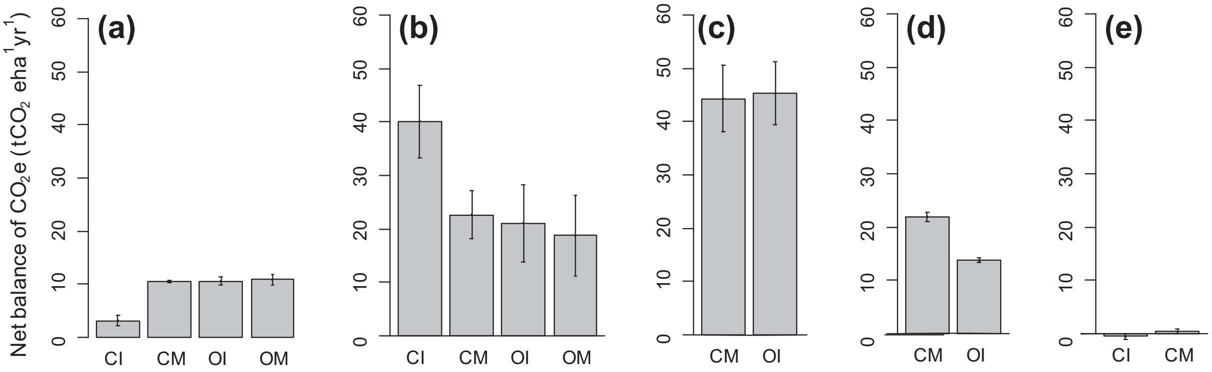

Fig. 2. Mean annual system net C balance (sum of sequestration into above-ground and below-ground biomass and litter minus the CF, tCO$_2$e ha^{-1} yr^{-1}) for the different shade types (a) *Erythrina poeppigiana* (E); (b) *Terminalia amazonia* (T); (C) *Chloroleucon eurycyclum* (c); (d) *E. poeppigiana*/*T. amazonia* (ET); (E) full sun (FS), combined with the four coffee management sub-plot treatments (defined in Fig. 1) which are arranged from the most intensive (left) to least intensive (right) in terms of quantity and quality of inputs. Whiskers indicate the upper and lower boundaries of the 84% confidence interval values (appropriate for judging significance of differences at $p < 0.05$).

experienced over the 10-year study period (50% higher prices) the opportunity cost to farmers of not converting to the most profitable intensive system overall (FS-CI, intensification scenario) rises considerably (by an average of 85% across shade types, Tables 2 and S6a). In contrast, the opportunity costs of not converting to the most intensive system dropped by an average of 47% across shade types when the analysis is conducted using minimum historic coffee prices (50% lower prices). Sensitivity analysis of the extensification scenario showed that, within each shade type, the deficit of maintaining less productive management compared to converting to the most profitable system only fell by 44% with the lower coffee price, but rose by 80% with the higher coffee price (Tables 2 and S6a). Sensitivity analysis over the 10 year study period of the intensification scenario for minimum and maximum labour costs showed a small increase of opportunity costs of 1% and 10% respectively (Table 2 and S6b). Sensitivity analysis of the extensification scenario showed that, the opportunity costs only fell by 3% with the lower labour costs, but rose by 6% with the higher labour costs (Tables 2 and S6b). Similarly, for low and high input costs over the 10 year study period (at the minimum and maximum 95% CI respectively) sensitivity analysis showed an increase of opportunity costs of 6% and 5% respectively of the intensification scenario whereas the results for the sensitivity analysis of the extensification scenario showed almost no change with a reduction of 1% in opportunity costs for low input costs and only a slight increase of 0.1% in opportunity costs for high input costs.

4. Discussion

4.1. Carbon balance, NPV and intensification

Carbon sequestration in above- and below-ground biomass for all shaded systems far outweighed the GHG emissions resulting from the farming of the coffee crop for all management intensities, and in some cases intensification even had a positive effect on the net C balance during these first 9 years of shade-tree growth through increased biomass accumulation (Table 1). The only negative net C balance was found in the intensively managed FS system. Similar results have been found in a previous study in Costa Rica comparing shaded and FS coffee systems, where the positive balance between C storage and non-CO$_2$ soil fluxes resulted in net storage of 11.93 and 2.67 tCO$_2$e ha^{-1} yr^{-1} respectively (compared to the corresponding values of +21.88 and −0.13 tCO$_2$e ha^{-1} yr^{-1} in the present study), on the assumption that initial above- and below-ground C biomass stocks were zero (Hergoualc'h, 2008). These results clearly indicate that coffee agroforestry systems can play an important part in climate change mitigation. This outcome will, however, depend on whether the starting C stocks at a site are actually zero and the balance over the complete lifetime of the coffee production system as the rate of C sequestration into above-ground C pools will reduce as trees and coffee bushes mature. As such, some divergence from these values of the first 9 years of coffee and shade-tree growth can be expected during the system's cultivation cycle.

Net Present Value of coffee production (ha^{-1} yr^{-1}) was positively correlated with CF (ha^{-1} yr^{-1}) and thus greater economic benefits to the farmer are accompanied by greater global environmental costs. We found, however, that some forms of intensification in coffee agroforestry systems could mitigate climate change both through increased C sequestration and also reducing the pressure for further land conversion to agricultural production. This supports findings that agricultural intensification can lead to a net reduction in overall GHG emissions (Burney et al., 2010) and that, in particular, agroforestry systems can play an important role in mitigating GHG emissions without compromising agricultural yields (Palm et al., 2010). This outcome, however, is strongly dependent on the shade type, its management and the fate of the additional wood production. Additional benefits of agroforestry systems, such as the provision of firewood (sometimes substituting for forest degradation or for the use of fossil fuels), could actually further increase their net positive contribution to climate change mitigation. Given the scale and effect of including the growth of standing biomass in calculation of the overall C balance of agricultural production systems, we conclude that current CF accounting methodologies should recognise this C sink in order to permit a more holistic representation of the footprint of entire supply chains.

4.2. LUC emissions and C markets

Our full economic analysis over the first 9 years of production showed that, in this experiment, under high intensity management FS systems are more profitable than high intensity shaded systems (E-CI and T-CI) with 5–35% greater NPV of coffee production (Table S5). This supports previous research which showed that when optimal growing conditions of FS exposure and high fertilisation rates are altered by the inclusion of shade trees, coffee production is reduced by up to 33% (Harmand et al., 2007). Current mechanisms such as REDD+ that are aimed at protecting existing forests and reducing GHG emissions by avoiding deforestation and forest degradation could be expanded to include agroforestry systems such as shaded coffee, incorporating payments to farmers

Table 1
Mean annual system net CO_2e balance (±SE based on variance amongst the three experimental blocks) for the LUC scenarios), for the five shade types (defined in Fig. 2) under the four different management treatments (defined in Fig. 1) after extensification.

Shade[a]	Management	CF[b] ($tCO_2e\ ha^{-1}\ yr^{-1}$)	C sequestered in biomass and litter ($tCO_2e\ ha^{-1}\ yr^{-1}$)	Annual net CO_2e balance ($tCO_2e\ ha^{-1}\ yr^{-1}$)	Annual net CO_2e balance of additional converted land (LUC + CF) ($tCO_2e\ ha^{-1}\ yr^{-1}$)	Annual net CO_2e balance after LUC ($tCO_2e\ ha^{-1}\ yr^{-1}$)
E	CI	6.13	9.21 (±1.28)	3.08 (±0.7)	0	3.08 (±1.3)
	CM	3.77	14.25 (±0.37)	10.48 (±0.2)	−30.31 (±10.8)	−19.84 (±10.5)
	OI	2.92	13.46 (±0.95)	10.54 (±0.5)	−100.32 (±78.5)	−89.78 (±78.5)
	OM	1.50	12.32 (±1.27)	10.82 (±0.7)	−19.42 (±8.9)	−8.60 (±8.2)
T	CI	5.14	45.24 (±9.07)	40.10 (±5.2)	0	40.10 (±5.2)
	CM	2.81	25.43 (±6.01)	22.63 (±3.5)	−13.82 (±10.5)	8.80 (±7.1)
	OI	1.72	22.74 (±9.51)	21.02 (±5.5)	−11.07 (±6.1)	9.96 (±10.5)
	OM	0.5	19.24 (±9.94)	18.74 (±5.7)	[c]	[c]
C	CM	2.95	47.24 (±8.22)	44.29 (±4.7)	0	44.29 (±4.7)
	OI	1.92	47.23 (±7.84)	45.31 (±4.5)	−147.63 (±121.5)	−102.33 (±122.1)
ET	CM	3.20	25.12 (±1.23)	21.92 (±0.7)	0	21.92 (±0.7)
	OI	2.29	15.97 (±0.58)	13.68 (±0.3)	−62.12 (±13.0)	−48.44 (±13.1)
FS	CI	5.00	4.43 (±0.45)	−0.57 (±0.5)	0	−0.57 (±0.5)
	CM	2.71	3.03 (±0.35)	0.32 (±0.4)	−5.32 (±4.1)	−12.04 (±9.8)

[a] Abbreviations are defined full in Fig. 2.
[b] Management inputs are considered the same across the three replicates and within the same sub-treatment and therefore show no SEM.
[c] No data shown as the mean NPV was negative and therefore LUC emissions due to additional land requirements could not be calculated.

by C-market mechanisms (Albrecht and Kandji, 2003; De Jong et al., 2004; Kandji et al., 2006; Soto-Pinto et al., 2010; Verchot et al., 2005, 2007). In agriculture, these mechanisms are usually based on changes in C stocks that are associated with changing from lower C-sequestration systems (e.g. FS) to higher net C-sequestration systems (e.g. shaded). Much coffee production in Central America, however, is already under shade which can store up to 100 tC ha^{-1} above- and below-ground (Verchot et al., 2007). Could C-market mechanisms be extended to pay farmers not to convert shaded to FS systems, or at least maintain their competitiveness against farmers in other parts of the world that do production under FS? The answer is complex: our results suggest that break-even prices, based on C sequestration rates, to avoid LUC from shaded to FS systems span a wide range from 9.3 to 196.3 US$ tCO_2e^{-1} sequestered, depending on the existing shade system. The maximum C-market prices of 11 and 15 US$ tCO_2e^{-1} paid for REDD+ and agroforestry projects in 2009 respectively (Hamilton et al., 2010) would only be sufficient to offset the opportunity cost borne by shaded systems that are already the most intensively managed and productive. Therefore, current financial incentives to reduce GHG emissions through increased shade cover in coffee systems may only be able to compete economically with FS systems when combined with intensive production methods. Shade trees can provide other economic benefits from timber and fuelwood and we recognise that our NPV analysis only considered income from coffee. Nevertheless, the summary of income from the tree component in coffee agroforestry systems by Idol et al. (2011) indicates that its income is rarely more than 20% of the value of the coffee harvest (this issue is explored further below). Although much current coffee production is managed under shaded systems that may not maximise NPV, this could change with predicted future increased commodity prices, land scarcity and population growth while accepting that many risk-averse farmers will still decide to retain shaded systems. With economic opportunities and individuals' responses continuing to be one of the main drivers of LUC (Lambin and Meyfroidt, 2011), reducing emissions by avoiding further LUC will have to present viable financial alternatives.

Evaluation of the economic contribution of timber trees on coffee farms in Costa Rica during the coffee price crash between 2000 and 2004 indicated the greater importance of this source of income in areas marginal for coffee production, where timber production contributed over 50% of income during this period, than in optimal coffee producing areas where it contributed only 6% (Dzib, 2003). One of these marginal coffee producing areas has received reforestation incentives from Costa Rica's Environmental Payments Scheme (COOPEAGRI, n.d.), though payments are made per tree planted rather than amount of C sequestered. Nevertheless, this has provided an incentive for farmers to introduce timber trees into over 300 ha of coffee and it is estimated that 8-year-old planting of *T. amazonia* has sequestered around 30 tC ha^{-1} into above-ground biomass (Dzib, 2003). However, farms with established shade systems have historically not received any such incentive for tree planting. To address this, in Costa Rica a new payment for established shade systems meeting certain criteria of tree density and diversity has recently been authorised to provide payments similar to those made for protected secondary forest (Cabrera, 2011). Nevertheless, to date there are no studies of the long-term dynamics of established shade systems to indicate whether or not they are still sequestering C. Such information would be critical to determine the viability of including such shade-coffee systems into the REDD+ process as a long-term sustainable mechanism to counteract economic pressures favouring intensification, and is therefore a priority for future research.

The sensitivity analysis supports the key assumption for this intensification scenario that higher coffee prices greatly favour a conversion from all shaded/low-input to high-input FS coffee (and low coffee prices disfavour this conversion). Similarly, the second sensitivity analysis shows that the economic benefit of conversion to the intensive system is generally greater when labour costs are higher, and less when they are lower, highlighting the importance of labour costs as a second factor in farmers' economic decision making. However, the third sensitivity analysis showed a much more complex outcome, the effect of increases or decreases of the costs of material inputs on the economic benefit of conversion to the intensive coffee production system varied greatly in direction amongst the shade types and management systems. To date, coffee farmers in Costa Rica have shown a divergence of responses to price and cost signals. However, as shown by the sensitivity analysis, the high levels of international coffee prices since 2010 are likely to make FS systems even more profitable. If these high prices are maintained, the opportunity costs of not converting to FS have the potentially to surpass the threshold of perceived risk which has stopped many farmers converting to this system before.

Table 2
Average farmer opportunity costs of not adopting a more intensive production system (intensification), or of adopting a more extensive production system (extensification), across shade types and coffee management systems under scenarios of historic minimum and maximum values of coffee prices, labour costs and input costs for the period 2000–2009. The values for each element separately, combination of shade and coffee management are shown in SI Tables S6a, S6b and S6c.

	Intensification scenarios			Extensification scenarios		
	Mean NPV	Minimum cost/price	Maximum cost/price	Mean NPV	Minimum cost/price	Maximum cost/price
Coffee	1337.92	707.02	2470.49	1075.11	605.75	1933.27
Labour		1373.58	1473.33		1041.42	1135.22
Input		1412.05	1408.06		1068.01	1076.46

Farmers' decision-making under uncertainty is heavily influenced by their perceptions of likely future changes in the market price of the commodities that they produce and labour and material inputs that they purchase. However, farmers know that these future prices are fundamentally unpredictable. Therefore farmers' perceptions of the future are heavily influenced by their recent past experience of levels and trends in prices/costs. We consider that this justifies our use of cost–benefit analysis based on the actual data of the past 9 years as the basis for testing scenarios about potential future LUC by coffee farmers in the study area.

4.3. 'Leakage' through extensification

The potential for C-market payments to coffee farmers to avoid intensification discussed above is based on an analysis confined to the existing farm system. However, it ignores the potential for a wider environmental impact of limiting production in this way mediated by the international coffee commodity market. We have shown that, if the modelled system is expanded to incorporate that effect through including the anticipated forest conversion LUC required to maintain the current profit from coffee production, the net effect on GHG emissions is strongly detrimental in approximately half the cases, i.e. it results in increased emissions. This illustrates how 'leakage' in the form of indirect LUC through extensification can have a considerable impact on the overall net C balance resulting from limitation to agricultural productivity. In reality, a reduction in coffee production in one location is unlikely to result in an exactly equal increase elsewhere (the degree of leakage will depend on the elasticity of both supply and demand for coffee), but some leakage is highly likely. The clearance of land in Vietnam and Indonesia to increase coffee production, could be seen, at least in part, as a result of the lack of capacity of Central American producers' to increase the productivity of their shaded coffee systems.

Leakage has already been identified as one of the main constraints to the success of REDD+: discontinuation or avoidance of economic activities in a project area being likely to cause the initiation or intensification of those activities in other areas (Dargusch et al., 2010; Martello et al., 2010). The present study shows why it is important that the effects of leakage should also be realistically incorporated into the planning of projects to reduce GHG emissions from current agricultural land. The continuing high prices of inputs such as fertilisers are a constraint on the alternative of agricultural intensification, though this constraint is likely to be overcome if economic incentives become viable for the farmer. However, without this intensification, there is also an increased risk that leakage from agricultural GHG emissions-reduction projects will be in the form of displaced deforestation (resulting in a potential net increase in GHG emissions and abrogation of the objectives of REDD+).

Burney et al. (2010) argue that the improvement and increase of crop yields can play a vital role in helping mitigate climate change within this wider land use context, and Fisher et al. (2011) suggest specifically that REDD+ payments could help finance the targeting of underlying drivers of deforestation by subsidising fertiliser, seed and agricultural training to increase yields on existing crop land. While likely to be limited by institutional and policy constraints, if successful this strategy could, therefore, not only contribute to mitigating climate change but at the same time keep pace with the increase in global demand for coffee. Therefore, a logical extension of REDD+ mechanisms to aid the success of climate change-mitigating agroforestry systems could be found in what we term '*reduced emissions through avoided land-use change*' (REAL). Adequate financial incentives through mechanisms such as REAL could therefore play an important role, not only in climate change mitigation, but also in helping to meet the millennium development goals of eradicating poverty and hunger. We do recognise that this study is limited to the trade-off in the ecosystem services of climate-change mitigation and food provisioning. We recommend that future studies should assess the trade-offs resulting from the impact of intensification on a wider range of provisioning, regulating and cultural ecosystem services. Whilst our results clearly indicate the benefits of conventional intensive shaded systems over FS systems in terms of climate change mitigation potential on currently farmed land, other drivers such as global demand for coffee and resulting financial incentives and policy development will determine farmers' decision-making over production system. This further highlights the need to combine efforts such as REDD+ with intensification or yield improvements in agricultural production.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2013.03.006.

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