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Intensification of coffee systems can increase the effectiveness of REDD mechanisms

Martin R.A. Noponen,†, Jeremy P. Haggar, Gareth Edwards-Jones, John R. Healey

School of Environment, Natural Resources and Geography, Bangor University, Bangor, Gwynedd LL57 2UW, United Kingdom
Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba 7170, Costa Rica
Natural Resources Institute (NRI), University of Greenwich at Medway, Chatham ME4 4TB, United Kingdom

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A B S T R A C T

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 tCO₂e 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 tCO₂e ha⁻¹ yr⁻¹ resulting in net emissions >8 tCO₂e 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 agro-forestry systems at the same time as aiding REDD through reducing pressure for further forest conversion to agriculture.

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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 po-
tential source of income (Laurance, 2007; Tollefon, 2008), in their
design it will be paramount to assess not only profitability but also
the potential for indirect GHG emissions through so-called “leak-
age”. 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. How-
ever, concerns about financial viability and competitiveness of REDD+ projects (Butler et al., 2009), and their potential to address drivers of
deforestation, are being voiced. Their wider success (including as-
pects of sustainable development, biodiversity conservation and
protection of existing forest lands) may depend on intensification
of existing agricultural land coupled with explicit policy interven-
tion (Ewers et al., 2009). Activities that address the causes of defor-
estation, 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 includ-
ing 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 doc-
umented and is often seen as an attractive option to combine cli-
mate 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 out-
weigh GHG emissions, making them carbon-neutral or even carbon-
negative systems throughout their productive lifetime. Coffee
production, however, depends on a combination of regional envi-
ronmental 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. In-
deed, 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 produc-
tion (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 Viet-
nam 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 pro-
ductivity, profitability and indirect impacts on land-use change.

This study evaluates the trade-off between profitability and cli-
mate 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 man-
agement systems under a range of shade tree types. We further ex-
plore how intensification affects the overall C balance and
profitability within shaded coffee production systems.

We firstly assess the impact of intensification on the relation-
ship 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 deter-
mining the difference in overall C balance amongst the systems.
We then calculate the price (in foregone revenue from coffee pro-
duction) 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 analy-
sis investigates the implications of LUC between forest and agricul-
ture 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-
aricultural, 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 calcu-
lated. 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), Turri-
alba, 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 eurycycrum (C); Terminalia
amazonia (T)) or combinations (E. poeppigiana + T. amazonia (ET))
of shade tree. The tree species were selected from those most com-
monly 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 man-
agement). The design is a randomised block with three blocks and
one replicate of each treatment per block. A more detailed descrip-
tion 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 dif-
ferent farming methods, the system boundaries were drawn at the
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 plant material and litter, below-ground C stock (Nabuurs et al., 2003). For all sampled living above-ground coffee biomass was calculated using an allometric equation developed by Dossa et al. (2008). 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).

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 and below-ground biomass and litter, including only those emissions directly associated with the production and management of a particular system. At the time of this study, the Publicly Available Specification 2050-2011 (PAS 2050), developed by the British Standard Institute, was the only globally recognised, transparent and publicly 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 (BRI, 2011). We recognise the limitations and uncertainties attached to the use of the fixed IPCC tier 1 assumptions about CO2 emissions, emission factors and models under such standards but consider these acceptable for the purpose of this analysis.

Within PAS 2050, fluxes of the GHGs CO2, N2O and CH4 are accounted for and converted into units of CO2 equivalents (CO2e) according to their global warming potential (GWP) over 100 years. Of specific relevance to agricultural CFs are non-CO2 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 CO2 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 CO2e.

2.5. Calculation of land-use change emissions

Land-use change emissions and sequestration of CO2 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-CO2 GHG emissions derived from sources such as manure, dead-wood, small-fraction litter and soils have also been included using 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 (Forsight, 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 CS, 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 (PVb) and the discounted present value of past costs (PVC). 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; Guel, 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 CO2e 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 CO2e 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 CO2e 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, CO₂e balance varies greatly between shade types (Fig. 2). Systems shaded by the single tree species *C. eurycyclum* had significantly higher (net fixation) C balance (tCO₂e 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.

### 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 tCO₂e 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 tCO₂e ha⁻¹ (*Table S5*) because of the huge variation in profitability (NPV) under the different shade types. 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 tCO₂e ha⁻¹) than organic (mean 116.9 US$ per sequestered tCO₂e 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 CO₂e 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 CO₂e 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 CO₂e balance (net emissions), up to 102 tCO₂e 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
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, all shaded systems far outweighed the GHG emissions resulting from the farming of the coffee crop for all management intensities, all shaded systems far outweighed the GHG emissions resulting from the farming of the coffee crop for all management intensities, all shaded systems far outweighed the GHG emissions resulting from the farming of the coffee crop for all management intensities, all shaded systems far outweighed the GHG emissions resulting from the farming of the coffee crop for all management intensities. Whiskers indicate the upper and lower boundaries of the 84% confidence interval values (appropriate for judging significance of differences at \( p < 0.05 \)).

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 optimal growing conditions of FS exposure and high fertiliser 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...
four different management treatments (defined in Fig. 1) after extensification. Mean annual system net CO2e 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 income from coffee. Nevertheless, the summary of income from fuelwood and we recognise that our NPV analysis only considered Shade trees can provide other economic benefits from timber and incentives to reduce GHG emissions through increased shade cover intensively managed and productive. Therefore, current financial opportunity cost borne by shaded systems that are already the most fertile system 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 1
Mean annual system net CO₂e 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.

<table>
<thead>
<tr>
<th>Shade</th>
<th>Management</th>
<th>C stored in biomass</th>
<th>C sequestered in litter</th>
<th>Annual net CO₂e balance after LUC</th>
<th>Annual net CO₂e balance of additional converted land (LUC + CF)</th>
<th>Annual net CO₂e balance after LUC (C sequestr.)</th>
<th>Annual mean NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CF</td>
<td>(tCO₂e ha⁻¹ yr⁻¹)</td>
<td>(tCO₂e ha⁻¹ yr⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>CI</td>
<td>6.13</td>
<td>9.21 (±1.28)</td>
<td>3.08 (±0.7)</td>
<td>0</td>
<td>3.08 (±1.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>3.77</td>
<td>14.25 (±0.37)</td>
<td>10.48 (±0.2)</td>
<td>–30.31 (±10.8)</td>
<td>–19.84 (±10.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OI</td>
<td>2.02</td>
<td>13.46 (±0.95)</td>
<td>10.54 (±0.2)</td>
<td>–100.32 (±78.5)</td>
<td>–89.78 (±78.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>1.50</td>
<td>12.32 (±1.27)</td>
<td>10.82 (±0.7)</td>
<td>–19.42 (±8.9)</td>
<td>–8.60 (±8.2)</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>CI</td>
<td>5.14</td>
<td>45.24 (±9.07)</td>
<td>40.10 (±5.2)</td>
<td>0</td>
<td>40.10 (±5.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>2.81</td>
<td>25.43 (±6.01)</td>
<td>22.63 (±3.5)</td>
<td>–13.82 (±10.5)</td>
<td>8.80 (±7.1)</td>
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<td></td>
<td>OI</td>
<td>1.72</td>
<td>22.74 (±9.51)</td>
<td>21.02 (±5.5)</td>
<td>–11.07 (±6.1)</td>
<td>9.96 (±10.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>0.5</td>
<td>19.24 (±9.94)</td>
<td>18.74 (±5.7)</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>CI</td>
<td>2.95</td>
<td>47.24 (±8.22)</td>
<td>44.29 (±4.7)</td>
<td>0</td>
<td>44.29 (±4.7)</td>
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</tr>
<tr>
<td></td>
<td>CM</td>
<td>1.92</td>
<td>47.23 (±7.84)</td>
<td>45.31 (±4.5)</td>
<td>–147.63 (±121.5)</td>
<td>–102.33 (±122.1)</td>
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</tr>
<tr>
<td></td>
<td>OI</td>
<td>1.39</td>
<td>19.97 (±5.08)</td>
<td>19.07 (±2.0)</td>
<td>0</td>
<td>21.92 (±0.7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>0.5</td>
<td>19.24 (±9.94)</td>
<td>18.74 (±5.7)</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ET</td>
<td>CI</td>
<td>3.20</td>
<td>25.12 (±12.13)</td>
<td>21.92 (±0.7)</td>
<td>0</td>
<td>21.92 (±0.7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>2.29</td>
<td>15.97 (±0.58)</td>
<td>13.68 (±0.3)</td>
<td>–62.12 (±13.0)</td>
<td>–48.44 (±13.1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OI</td>
<td>1.22</td>
<td>9.57 (±1.34)</td>
<td>8.60 (±0.5)</td>
<td>0</td>
<td>–58.05 (±0.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>0.5</td>
<td>19.24 (±9.94)</td>
<td>18.74 (±5.7)</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS</td>
<td>CI</td>
<td>5.00</td>
<td>4.43 (±0.45)</td>
<td>0.57 (±0.5)</td>
<td>0</td>
<td>–58.05 (±0.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>2.71</td>
<td>3.03 (±0.35)</td>
<td>0.32 (±0.4)</td>
<td>–5.32 (±4.1)</td>
<td>–12.04 (±9.8)</td>
<td></td>
</tr>
</tbody>
</table>

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

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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.

Acknowledgements

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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.

References


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.

<table>
<thead>
<tr>
<th>Intensification scenarios</th>
<th>Extensification scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean NPV</td>
<td>Minimum cost/price</td>
</tr>
<tr>
<td>Coffee</td>
<td>1317.92</td>
</tr>
<tr>
<td>Labour</td>
<td>1373.58</td>
</tr>
<tr>
<td>Input</td>
<td>1408.06</td>
</tr>
<tr>
<td>Mean NPV</td>
<td>1075.11</td>
</tr>
<tr>
<td>Minimum cost/price</td>
<td>1041.42</td>
</tr>
<tr>
<td>Maximum cost/price</td>
<td>1068.01</td>
</tr>
</tbody>
</table>