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Cocoa Intensification Scenarios and Their Predicted Impact on CO_2 Emissions, Biodiversity Conservation, and Rural Livelihoods in the Guinea Rain Forest of West Africa

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Abstract The Guinean rain forest (GRF) of West Africa, identified over 20 years ago as a global biodiversity hotspot, had reduced to 113,000 km^2 at the start of the new millennium which was 18% of its original area. The principal driver of this environmental change has been the expansion of extensive smallholder agriculture. From 1988 to 2007, the area harvested in the GRF by smallholders of cocoa, cassava, and oil palm increased by 68,000 km^2. Field results suggest a high potential for significantly increasing crop yields through increased application of seed-fertilizer technologies. Analyzing land-use change scenarios, it was estimated that had intensified cocoa technology, already developed in the 1960s, been pursued in Cote d'Ivoire, Ghana, Nigeria and Cameroon that over 21,000 km^2 of deforestation and forest degradation could have been avoided along with the emission of nearly 1.4 billion t of CO_2. Addressing the low productivity of agriculture in the GRF should be one of the principal objectives of REDD climate mitigation programs.

Keywords Land saving · Fertilizer · Agricultural intensification · Deforestation · Poverty · REDD

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Introduction

Though tropical rainforests only cover 7% of the earth's land surface, they are estimated to contain at least one-third of global plant and animal biodiversity (Dirzo and Raven 2003). Tropical forest conversion to agricultural land uses accounts for the largest share of annual greenhouse gas emissions due to land use change (Houghton 1999) and threatens massive extinction with an estimated 27,000 species lost each year (Wilson 2002). In much of the humid tropics, the expansion of agriculture by poor smallholders is the leading driver of deforestation (Geist and Lambin 2001; Norris and others 2010); and raising the poor to a decent standard of living without, at the same time, destroying most of life is, according to Wilson (2002), the most urgent challenge facing the global environmental movement.

The West African Guinea Rainforest (GRF) stretching from Guinea to Cameroon is a priority challenge identified 20 years ago as a global biodiversity hotspot (Myers 1990; Myers and others 2000; Conservation International 2007). Less than 18% of the original GRF still stands as dense forest (Mayaux and others 2004) as the nutrients of the GRF have been progressively mined by millions of poor households employing rudimentary slash-and-burn technology. Paradoxically, these same households depend on stocks of wild foods, fuelwood, and traditional medicines, which are produced by the forests they cut down and burn in their agricultural practice.

The main focus of the paper is an empirical investigation of the tradeoffs between productivity and deforestation for cocoa production systems at various levels of input intensification and land productivity in the GRF. A spreadsheet model of cocoa production, land use changes, and carbon stocks investigates counterfactual scenarios of cropping intensification. From the results of this retrospective analysis, an operational plan is proposed and discussed for increasing land productivity through intensification in order to conserve the remaining reserves of the GRF while addressing rural poverty.

Materials and Methods

Cocoa, *Theobroma cacao* L., in West Africa is traditionally grown under a shade canopy which typically produces fruit and timber as secondary products that can attain a certain economic significance in some localities (Oke and Odebiyi 2007; Gockowski and others 2010). Extensive shaded cocoa has environmental values that are higher than most other agricultural land uses, but still remain significantly lower than the original forest (Gockowski and others 2005; Oke and Odebiyi 2007; Schroth and Harvey 2007). The better environmental performance of these systems has led to calls for their expansion as potential win-win solutions for economic growth and environmental services (Gockowski and others 2005; Sonwa and others 2007).

The main focus of cocoa research programs in West Africa has been the development of fertilized, low shade/full sun hybrid cocoa systems with little attention to the performance of intensified cocoa-timber or cocoa-fruit associations. In Ghana, CRIG, the national cocoa research institute, currently recommends the application of 371 kg ha^{-1} of 0–18–23 NPK fertilizer plus micronutrients to hybrid cocoa planted at 1,111 trees per ha with a maximum shade tree density of 12–15 trees per ha. While the technical superiority of this low shade hybrid cocoa technology has been demonstrated on research stations for over 30 years, adoption of the full package has been limited. Of the three main elements of the technology package (improved seed, fertilizer, and low shade) it is often only the elimination of shade that is practiced by resource-poor farmers who are either unable to afford, or lack ready access to the fertilizers and hybrid germplasm that are the key factors in the long term sustainability and productivity of this system.

Field and experimental station results inform spreadsheet models that predict the areas of dense forest, cocoa harvested and their combined carbon stock for various productivity scenarios. These estimates are compared to the carbon stock and area of extant dense forest and cocoa production systems in the GRF. An income analysis of the alternative technology systems under three price policy regimes is also conducted.

Growth Trends of Production, Yield, and Area Harvested

To establish the relative importance of extensive agricultural practice in the GRF, the trends (or lack thereof) in yields, total output, and area harvested of cocoa, cassava (*Manihot esculenta* Crantz), oil palm (*Elaesis guinensis* Jacq.), robusta coffee (*Coffea canephora* Pierre), rubber (*Hevea brasiliensis* Mull.-Arg.), plantain (*Musa* × *paradisiaca* AB), and taro & cocoyam (*Colocasia esculenta* (L.) Shott and *Xanthosoma sagittifolium* (L.) Shott) were estimated by least-squares growth regressions. Trend analysis was conducted on a regional aggregation of the seven countries of the GRF (Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Ghana, Nigeria and Cameroon) using FAOSTAT data from 1988 to 2007.

Measures of Carbon Stocks and Biodiversity

Our measures of carbon stocks and biodiversity are drawn from field studies conducted in the forest margins of southern Cameroon from 1997 to 1999 (Gockowski and others 2005). Carbon stocks at the plot level were sampled using standardized protocols across all program sites (Woomer and Palm 1998; Woomer and others 1999; Palm and others 2000, 2005). The protocols used a biomass estimation method for tropical forests developed by Brown and others (1989) based on diameter at breast height (DBH) measures. The total area sampled for tree biomass at each site was 500 m^2. The above- and below-ground C estimates for shaded cocoa land uses and forest land cover were obtained from five field site replicates (in each field site, estimates were obtained from an average of five quadrats or pseudo-replicates). Changes in root carbon were assumed to be proportional to the changes in above-ground carbon across land use systems. Soil carbon was measured in the first 20 cm of the soil horizon.

To compare the carbon stocks and emissions of land-use systems like cocoa agro-forests and crop-fallow rotations which emit carbon in one large quantity at field establishment and then accumulate carbon over time at differential rates and over differing time periods, Palm and others (2005) measured time averaged carbon stocks, *TACS*, which is the sum of the annual carbon stock measured in tons ha^{-1} of the land use system divided by the production cycle (t) of the system. Mathematically, the time averaged carbon stock ($TACS_i$) of land use system i is the mean integral of the continuous function f_i describing the annual change in the carbon stock of land use i over the production cycle t:

$$TACS_i = \frac{\int_0^t f(t)dt}{t}$$

Assuming that the land use system i involves the conversion of dense forest, the net carbon emitted in the conversion to land use system i is the difference in the time averaged carbon stock of the dense forest and that of land use system i:

$$Net\ C\ emission = TACS_{forest} - TACS_i.$$

We use this relationship in combination with FAO information on area harvested to estimate the time-averaged carbon stock in cocoa production in the GRF for the 2007 baseline values of shaded cocoa, full sun cocoa, and dense forest. We then compare the baseline results to three alternative production scenarios.

A standard rapid appraisal protocol for measuring plant biodiversity was implemented across a gradient of land uses ranging from forest to agroforest to long fallow and short fallow crop rotations. In Cameroon, plant biodiversity was assessed for three cropping systems (short fallow mixed food crop, long fallow mixed food crops, and cocoa agroforests) and forest in 21 sites. Randomly assigned transects of 40 m × 5 m were split into eight 5 m × 5 m quadrats and data collected on all vascular plant species and unique plant functional types (Gillison 2000). A total of four forest and two cocoa agroforest sites were sampled.

Cocoa Producer Surveys

Estimates of the extent of shaded versus full sun cocoa systems were obtained from a production survey implemented in the major cocoa producing areas of Cameroon, Ghana, Côte d'Ivoire, and Nigeria in 2001/2002 (Fig. 1). Villages were randomly selected without replacement using a balanced cluster design from preselected cocoa producing districts known in the aggregate to account for 80% of national production. The district sample size was proportional to its output. In the second stage, systematic sampling of households was implemented after the random selection of the first household. Plot specific information was collected on a total of 6,430 spatially distinct cocoa production systems through interviews with 4,458 household heads in 329 villages. Among other things, the survey queried the producer on the presence or absence of shade for each cocoa plot.

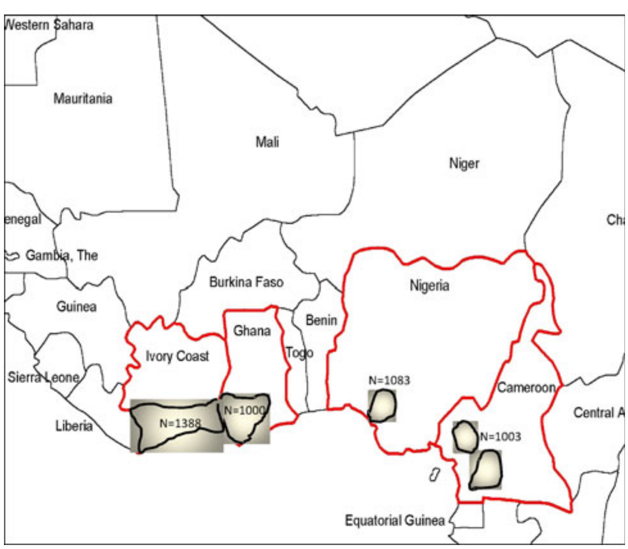

Fig. 1 Approximate locations and sample size of the 2001/2002 cocoa producer surveys in West Africa

In addition to the producer survey, a field investigation of cocoa yield, shade tree densities, and input use was conducted in Côte d'Ivoire and Ghana in 2009. From this investigation a total of 119 cocoa producers whose farms were in a mature productive phase between 8 and 26 years at the time of the survey were analyzed. The age of the farm was purposively chosen to minimize yield variation due to age effects. Field size was measured for all farms with handheld GPS devices and in each farm randomized transects totaling 800 m^2 per farm were used to estimate shade tree and cocoa density. Shade trees were defined as any tree with more than 50% of its canopy above the cocoa canopy and full sun cocoa was defined as any farm with fewer than 13 shade trees per ha. Farmers operating these enterprises were interviewed to determine their 2008/2009 output and expenditures on fertilizers and insecticides. The collected data were used to estimate OLS regression models of cocoa yield per ha of cocoa land specified as:

$$Yld_i = a_0 + b_1Fert_i + b_2Insect_i + b_3Ecozone_i + b_4Fullsun_i + e_i$$

where Yld_i, the 2008/2009 total marketed production of producer i divided by the number of ha in production; $Fert_i$, the 2008/2009 total kilograms of fertilizer applied by producer i divided by the number of ha in production with b_1 hypothesized to be positive; $Ecozone_i$, a locational dummy variable differentiating more favorable eco-regions from less favorable with b_3 hypothesized to be positive; $Insect_i$, the local currency value of 2008/2009 insecticide expenditures applied by producer i divided by the number of ha in production with b_2 hypothesized to be positive; $Fullsun_i$, 1 if estimated shade tree density of producer i is <13 trees per ha, and 0 if density is ≥ 13 trees with b_4 hypothesized to be positive; e_i, the residual error of producer i.

The model is used to estimate the impact of shade and intensified use of inputs on yield and to validate the results obtained in the 1960s and 1970s by the Cocoa Research Institute of Ghana (Ahenkorah and others 1987).

Results

Agricultural Growth Trends

The importance of extensive agricultural growth as a driver of deforestation and forest degradation in the GRF as documented by Geist and Lambin (2001) and Norris and others (2010) is supported by the trend analysis. With the exception of robusta coffee, annual growth in production, which is identically equal to the growth rate in area plus the growth rate in yields, was positive and significant for all commodities considered and was predominantly due to area expansions (Table 1). Cassava, the principal staple commodity in West Africa and the commodity with the largest increase in area harvested has experienced essentially no change in yields over the last 20 years. Yield growth for oil palm, which witnessed the third largest absolute increase in area, was negative. Cocoa and plantain, which are second and fourth in terms of area expansion, did show some positive yield growth although it only accounted for 16 and 20%, respectively, of the total increase in the production of these crops. The low growth in crop yields is evidence of a continuing reliance on extensive "land consuming" rather than "land saving" technology systems in West Africa.

Table 1 Mean growth rates in area harvested, yields and total output for the selected commodities of the Guinea Rainforest of Guinea, Sierra Leone, Liberia, Cote d'Ivoire, Ghana, Nigeria and Cameroon, 1988–2007

Crop	Area harvested (%)	Yield (%)	Production (%)
Taro	3.61***	4.12***	7.72***
Cassava	4.08***	0.06$^{n.s.}$	4.14***
Cocoa	3.29***	0.64***	3.93***
Plantain	3.01***	0.74***	3.75***
Rubber	2.01***	1.32***	3.33***
Oil palm	2.21***	−0.22**	1.99***
Coffee	−3.08***	1.55**	−1.53*

Source: FAOSTAT|© FAO Statistics Division 2009|06 December 2009

n.s. not significant

* $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$

Overall the area harvested of the seven commodities studied increased by 7.4 million ha from 1988 to 2007 (Table 2). Agricultural expansion was particularly pronounced for food crops reflecting the rapid growth of urban populations (4.2% per annum from 1987 to 2009) in the GRF countries and their associated food demands, particularly for convenient staple foods such as cassava gari, cassava foufou, rice, and plantain. Cocoa had the greatest surface area harvested in 2007, followed closely by cassava and then oil palm.

Cocoa production in West Africa is an important commercial activity that links over 2 million GRF households to the global economy. For the last 20 years Côte d'Ivoire has been the largest producer both in terms of output and numbers of producers, followed by Ghana, Nigeria, and Cameroon with these four countries now accounting for 70% of global supply.

Deforestation, Forest Degradation and the Cocoa Smallholder

As seen, cocoa is the most widespread land use system in the GRF and the increase in the area harvested over the last 20 years has resulted in the deforestation and degradation of approximately 2.3 million ha of GRF. The magnitude of the environmental impact of this deforestation/degradation episode depends upon: (a) the land use prior to cocoa establishment, (b) the diversity and extent of the forest canopy maintained for permanent shade, and (c) the way in which the farm is established. The analysis now focuses on the four largest producers of cocoa in the GRF, namely, Côte d'Ivoire, Ghana, Nigeria and Cameroon, together

Table 2 Area planted to selected commodities of the Guinea Rainforest of Guinea, Sierra Leone, Liberia, Cote d'Ivoire, Ghana, Nigeria and Cameroon, 1988–2007

	1988–1990		2005–2007		Change in mean area (ha)	Percentage of total change
	Mean area (ha)	Percentage of total	Mean area (ha)	Percentage of total		
Cassava	2,497,106	21	5,663,173	29	3,166,066	43
Plantain	932,210	8	1,503,741	8	571,531	8
Taro	685,345	6	1,253,889	6	568,545	8
Food crops	4,114,661	34	8,420,803	43	4,306,142	58
Cocoa	3,432,269	29	5,723,960	29	2,291,691	31
Coffee	1,596,267	13	1,060,460	5	(535,807)	−7
Oil palm	2,821,570	23	4,141,098	21	1,319,528	18
Rubber	46,542	0	62,179	0	15,637	0
Tree crops	7,896,647	66	10,987,697	57	3,091,050	42
Total	12,011,308	100	19,408,500	100	7,397,191	100

Source: FAOSTAT|© FAO Statistics Division 2009|06 December 2009

Table 3 Type of cocoa production, land use prior to establishment, type of establishment, quality of planting material and planting technique in the cocoa sectors of Cote d'Ivoire, Ghana, Nigeria and Cameroon, in 2001

	Cameroon Proportion of farms	Côte d'Ivoire	Ghana	Nigeria
Type of cocoa production system				
Full sun	0.081	0.279	0.281	0.03
Shaded	0.919	0.721	0.719	0.97
Land cover/use prior to cocoa establishment				
Forest	0.784	0.719	0.298	0.560
Fallow	0.209	0.269	0.675	0.437
Savanna	0.007	0.012	0.027	0.003
Cocoa establishment field type				
Understory planting into thinned forest	0.591	0.210	0.195	0.648
Slash and burn field establishment	0.409	0.790	0.805	0.352
Cocoa planting material				
Improved	0.179	0.135	0.42	0.093
Unimproved from own tree stock	0.879	0.912	0.728	0.931
Planting technique				
Seeded directly into field	0.499	0.578	0.912	0.46
Transplant polybag seedling	0.551	0.587	0.142	0.119
Transplant bareroot seedling	0.392	0.157	0.09	0.732

Source: 2001/2002 IITA STCP producer survey

these countries accounted for 88% of the 5.7 M ha cocoa area harvested in 2007.

The producer survey in the four countries found that most cocoa was grown under shade (Table 3). Ghana and Côte d'Ivoire had the highest frequency of producers declaring full-sun production systems, although in both cases the proportion was under 30%. Overall 79% of the area planted to cocoa by survey respondents included permanent shade, while 21% were classified as full sun. Forest was indicated as the previous land cover prior to cocoa by a majority of producers in Cameroon, Nigeria and Côte d'Ivoire (Table 3). In Ghana where rural population pressures are high, the most common land use transition was from bush fallow to cocoa. The least common transition was from savanna to cocoa. Cocoa farms were most typically established either by slashing and burning the forest and then planting cocoa (Côte d'Ivoire and Ghana), or by planting under a thinned forest over-storey (Cameroon and Nigeria) (Table 3). Farms created following slash and burn episodes will typically have a lower mean carbon stock and thus higher emissions than will farms planted under a thinned over-storey, because the above ground biomass is near zero at the start of the production cycle for the former.

Intensification of cocoa production is an important objective to increase productivity and farm income; and the replacement of ageing tree stocks with improved planting material is a key element in this process (Edwin and Masters 2005). The survey found that by and large farmers did not use improved planting material instead using seedlings from their own tree stocks for establishing cocoa farms (Table 3).

Measures of Shade Density and Tree Biodiversity

A review of West African studies quantifying non-cocoa tree density and plant/tree species richness gives an overview of the structure and diversity of shaded cocoa relative to forests (Table 4). In general the density and diversity of shade trees on cocoa farms reached its highest levels in Cameroon. Zapfack and others (2002) compared the shaded cocoa systems of Cameroon with forest and found that the non-cocoa tree density was 38% that of the forest, while the vascular plant species richness measure was 70% of the mean forest level. In a similar study in Nigeria the density of shade trees on cocoa farms was less than 10% of the forest tree density (Oke and Odebiyi 2007).

The shaded cocoa systems of the Center Province of Cameroon consist of mixed associations of cocoa, timber and fruit trees (Sonwa 2004; Gockowski and others 2010). The five most common tree species encountered in these forests are avocado (*Persea americana*), African plum (*Dacryodes edulis*), mango (*Mangifera indica*), oil palm and *Terminalia superba* (Engl. & Diels) all of which have economic value. Oil palm and the African plum comprised the largest part of non-cocoa revenues, which in total accounted for 23% of the overall revenues from shaded cocoa production systems (Gockowski and others 2010).

Table 4 Non-cocoa tree density and plant species identified in shaded cocoa systems and secondary forest across West Africa

Country	Study authors	Land use evaluated	Shade trees (ha)	Species identified	Area sampled (ha)	Notes
Cam.	Zapfack and others (2002)	Cocoa	120	116		a, e, h
	Zapfack and others (2002)	Sec. forest	328	171		a, e, h
	Zapfack and others (2002)	Pri. forest	296	160		a, e, h
Cam.	Sonwa (2004)	Cocoa	256	206	9.1	b, e
Cam.	Gockowski and others (2010)	Cocoa	131	286,176	67	c, f, g
Nig.	Oke and Odebiyi (2007)	Cocoa	23	45	21	c, f
	Oke and Odebiyi (2007)	Sec. Forest	256	62	0.56	
Gha.	Osei-Bonsu and others (2003)	Cocoa	33–111	116	60	d, f
Cdl	N'goran (1998)	Mature cocoa	52–56			d, h, i
	N'goran (1998)	Young Cocoa	16–17			d, h, i
Cdl	Ruf and Schroth (2004)	Cocoa (migrants)	21			d, h, i
	Ruf and Schroth (2004)	Cocoa (locals)	37			d, h, i
Cdl	Herzog (1994)	Cocoa	6			d, h, i

Source: Compiled by authors

a minimum tree diameter >15 cm DBH, *b* minimum tree diameter >2.5 cm DBH, *c* minimum tree diameter >10 cm DBH, *d* minimum tree diameter not specified, *e* all plant species, *f* only tree species, *g* timber and non-timber forest product (NTFP) species used by local population, *h* area sampled not given, *i* species not enumerated

Cocoa Yields

Long-term research trials at the Cocoa Research Institute of Ghana provide empirical measures of fertilizer and shade effects on yields (Ahenkorah and others 1987). Three shade treatments and three levels of N, P and K were compared using Amazon hybrid cocoa planted at a uniform density of 1,076 stems per ha. *Terminalia ivorensis* was planted as permanent shade at two shade densities: $S_1 = 67$ stems per ha and $S_2 = 269$ stems per ha. The shade densities were adjusted to $S_1 = 34$ stems per ha, and $S_2 = 134$ stems per ha 12 years after planting. The shade treatments were compared to a full sun (S_0) system. Cumulative production of marketable cocoa was 16.7, 11.4 and 7.89 t ha^{-1} for S_0, S_1 and S_2 over the 20 years of the trial, i.e., S_1 and S_2 yields were equivalent to 68 and 47% of S_0 yields.

Average cocoa yields in Ghana were more than double those of Ivoirian farmers which appears to be related to a higher incidence of full sun production systems, and more substantial applications of fertilizer and insecticide (Table 5). Thirty-three and 49% of sampled producers in Ghana and Côte d'Ivoire, respectively, were not applying any agrochemicals. Only 13% of Ivoirian producers interviewed reported using fertilizer in 2008/2009 and among these producers the mean quantity applied was only 27 kg ha^{-1}. In Ghana, although only used by 17% of sampled producers, the mean quantity of fertilizer applied was nearly 60% of the recommended rate of 370 kg ha^{-1} (Table 6). In both countries, similar compound formulations were available though the unsubsidized price in Côte d'Ivoire was significantly higher than the subsidized price in Ghana ($37.80 vs. $10.80 per 50 kg bag).

In both countries, insecticide expenditures to control capsid insects had a significant effect on yields in the regression model and were applied by 50 and 63% of producers sampled in Côte d'Ivoire and Ghana. Not surprisingly, fertilizer use in Côte d'Ivoire did not have a significant effect on yield reflecting its limited use and low application rate whereas in Ghana there was a significant positive impact ($P < 0.01$, Table 5). In both countries the regression models reveal significant yield suppressing shade effects ($P < 0.05$). The mean non-cocoa tree density was 48 and 94 trees per ha in Ghana and Côte d'Ivoire, respectively. The predicted yields for full sun and shaded production systems under extensive, mean input use and intensive use of inputs are compared in Fig. 2. The mean predicted yield among producers in the extensive use class was less than half of the yield predicted for the intensified producers. The cocoa yields of shaded systems at the mean level of input use were equal to 69 and 52% of the full sun systems in Ghana and Côte d'Ivoire. In a similar line of research, Steffan-Dewenter and others (2007) report lightly shaded cocoa yields were 60% of full sun systems in Indonesia. Figure 2 suggests the feasibility of significantly increasing the yields of both the full sun and shaded production systems through intensification.

Carbon Stock and Biodiversity Measures

The ASB biodiversity and carbon stock measures for forest, shaded cocoa, and full sun systems of southern

Table 5 Cocoa yield regressions for Ghana ($n = 60$) and Cote d'Ivoire ($n = 59$) for productive farms established between 8 and 26 years prior to the 2008/2009 harvest

Country/variable	Descriptive statistics			OLS			
	Mean	SD	Max	Coeff.	SE	*t* test	Prob.
Ghana							
Yld (kg/ha)	456	272	1140				
Ecozone (0,1)	0.317	0.469	1	5.2	70.1	0.07	0.941
Fert (kg/ha)	36.7	92.5	381	0.315	0.109	2.89	0.005
Insect (GhC/ha)	11.1	18.5	86.6	2.71	1.79	1.52	0.135
Fullsun (0,1)	0.233	0.426	1	172	74.4	2.31	0.025
Constant				345	43.1	7.99	0
Country/variable	**Descriptive statistics**			**OLS**			
	Mean	SD	Max	Coeff.	Robust SE	*t* test	Prob.
Cote d'Ivoire							
Yld (kg/ha)	214	173	710				
Ecozone (0,1)	0.407	0.495	1	68	43.6	1.56	0.125
Fert (kg/ha)	3.7	15.8	87.6	−0.665	1.33	−0.5	0.619
Insect (FCFA/ha)	5,060	15,700	119,000	0.0019	0.0011	1.73	0.09
Fullsun (0,1)	0.186	0.393	1	169	71.3	2.38	0.021
Constant				147	24.2	6.08	0

Adj. $R^2 = 0.269$, Breusch-Pagan test for heteroskedasticity $\chi^2(1) = 0.05$

Adj. $R^2 = 0.220$, Breusch-Pagan test for heteroskedasticity, $\chi^2(1) = 4.05$

Ecozone variable in Ghana is defined as 1 if farm location is Western Region, 0 if Ashanti Region. In Cote D'Ivoire *ecozone* is defined as 1 if farm location is either Bas Sassandra, Haut Sassassandra, Lagunes, Sud Bandama or Sud Comoe regions and zero if farm location is either Agneby, Moyen Comoe or N'Zi Comoe regions. *Fullsun* is defined as = 1 if non cocoa tree density is less than 13 trees per ha, 0 otherwise. 1 USD = GhC 1.37 and 1 USD = 476 FCFA in 2008/2009 season

Table 6 Fertilizer application on cocoa in Ghana and Cote d'Ivoire in kg ha^{-1}

Parameter	RCI	Ghana
Mean	27.3	213
Percentage of CRIG recommended rate	7	57
SD	36.4	106
Min	5.20	27.5
Max	87.7	381
N	8	10
Percentage of sample applying	14	17

In Ghana, the fertilizer formulation was NPK (0–22–18) + 7S + 6MgO + 9CaO, while in Cote d'Ivoire it was NPK (0–23–19) + 6.5 S + 5MgO + 10CaO

Source: 2009 IITA STCP producer evaluation survey

Cameroon are presented in Table 7. The values of the forest and soil carbon stocks were assumed to be in equilibrium and unchanging. The mean aboveground *TACS* for shaded cocoa is calculated based on a 40 year production cycle with the above-ground carbon stock maintained at an equilibrium value of 88.7 t C ha^{-1} from year 25 to 40 and an annual sequestration rate of 3.55 t C ha^{-1} from year 1 to year 25. The overall *TACS* is equal to the aboveground *TACS* plus the soil C stock. The *TACS* for full sun cocoa was based on a 25-year production cycle with an annual sequestration rate of 1.96 t C ha^{-1} from year 1 to year 25. We assumed a shorter production cycle for full sun cocoa because of reported early senescence that is believed to be

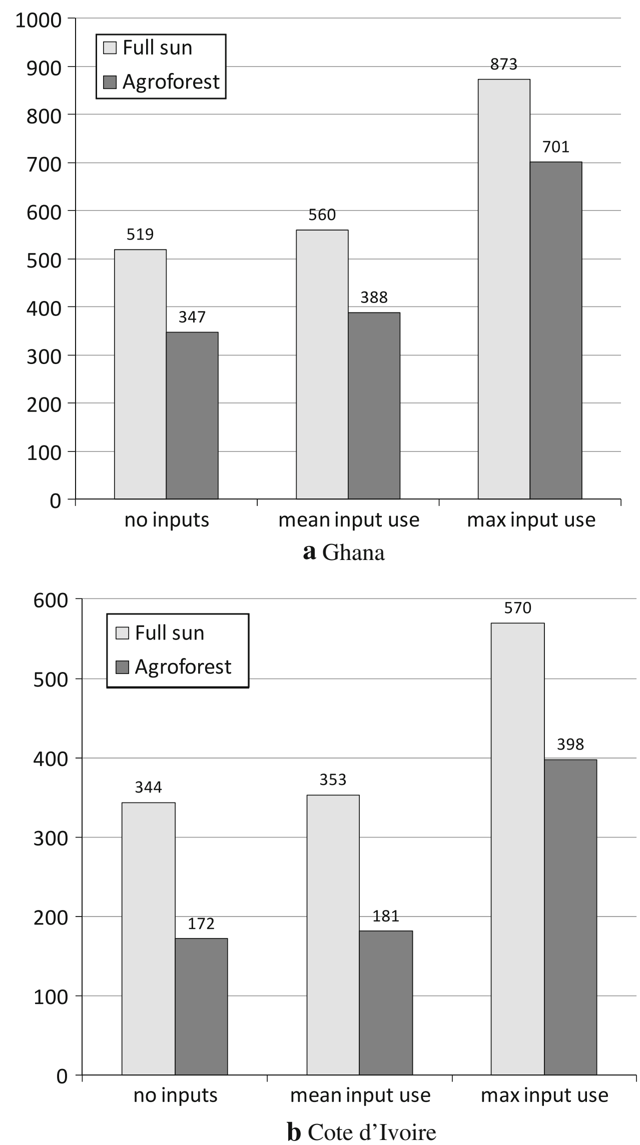

Fig. 2 Predicted cocoa yield under three levels of input by type of production system for **a** Ghanaian and **b** Ivoirian producers in 2009. Panel a—*no inputs* (33% of sample), *mean input use* (36.7 kg ha^{-1} of fertilizer and GhC 11.1 ha^{-1} of insecticides) and *max input use* (381 kg ha^{-1} of fertilizer and GhC 86.6 ha^{-1} of insecticides). Panel b—*no inputs* (49% of Ivoirian sample), *mean input use* (f CFA 10,100 ha^{-1} of insecticides) and *max input use* (f CFA 119,000 ha^{-1} of insecticides)

Table 7 Mean time averaged carbon stock and plant biodiversity in full sun cocoa, cocoa agroforest, and forest land uses in southern Cameroon (standard errors in parentheses)

Land use	Above ground C stock (t/ha)	Above ground *TACS* (t/ha)	Below ground C stock (t/ha)	Overall *TACS* (t/ha)	Mean number of vascular plant species (species/200 m)
Forest	227 (12.0)	227 (12.0)	45.4 (3.78)	273 (14.2)	75.8 (13.1)
Cocoa agroforest	88.7 (14.1)	61.0 (9.71)	43.2 (3.63)	104 (11.1)	71.5 (8.50)
Full sun cocoa	49.1 (7.13)	24.5 (3.56)	43.2 (3.63)	67.7 (6.44)	

Notes: As full sun cocoa is difficult to find in Cameroon, we used the above ground cocoa tree carbon stocks for farms classified as low shade systems (shade tree density (2.5 cm DBH) <100/ha) for our full sun cocoa estimate. As such this estimate probably underestimates the value for a full sun system because of the negative impact of shade on cocoa tree growth

associated with their higher yields (Ahenkorah and others 1987). The mean *TACS* of shaded and full sun cocoa were estimated to be 38 and 25% of the forest *TACS*, respectively.

In contrast with the results for carbon, differences in the species richness of vascular plants were less pronounced (Table 7). The number of vascular plant species was not included in the full sun analysis due to the lack of full sun systems in the ASB field sites. However, given the monoculture nature of full sun cocoa and the self mulching facility of these systems once the cocoa canopy is closed, there should be a clear and distinct decline in the species richness of vascular plants relative to the extensive shaded system. From a cocoa productivity standpoint, species richness is likely correlated with competition for sunlight, water, and nutrients and therefore negatively correlated with output.

The Impact of Current and Alternative Technology Systems on Land Use Change

The deforestation, forest degradation and associated environmental change incurred in producing 2.65 million tons of cocoa per annum are estimated using the findings on the cocoa sector presented above. Counterfactual analyses examine the hypothetical deforestation, forest degradation and associated environmental change that would have occurred had alternative production technologies been utilized in the production of 2.65 million tons. Three alternative production scenarios are considered: the first involves the replacement of all full sun cocoa with extensive shaded cocoa systems; the second considers the replacement of all extensive full sun and shaded cocoa systems with intensified cocoa-timber systems; and in the third scenario, all extensive full sun and shaded cocoa systems are replaced with a mix of intensified full sun production systems and intensified cocoa-timber systems.

A 58% differential in yield between full sun and shaded cocoa is assumed as reported by Ahenkorah and others (1987). This value is very similar to the difference reported above from the Ghana and Côte d'Ivoire field surveys and closely matches findings from Indonesia (Steffan-Dewenter and others 2007). Using the ratio of shaded to full sun cocoa from the 2001/2002 producer survey and the average yield of 529 kg ha^{-1} reported by FAOSTAT, the area harvested and output of extensive full sun and extensive shaded cocoa was estimated (Table 8). The adjusted cocoa yields are 459 and 792 kg ha^{-1}, respectively for the extensive shaded and full sun cocoa production systems and a total area of 5.1 M ha is in production.

The intensification scenarios involve the application of 0–18–23 NPK cocoa fertilizer and approved pesticides at the rates currently recommended by research. Based on the 2009 fertilizer response estimates from the Ghanaian regression model, the cocoa yield of the intensified full sun cocoa system was assumed to increase by 64% from 792 to 1,234 kg ha^{-1} and the cocoa yield of the intensified cocoa-timber system by 55% from 459 to 829 kg ha^{-1}.

For the 2007 baseline scenario it is estimated that approximately one million ha of the GRF has been deforested by the production of full sun cocoa and almost 4 million ha has been degraded by the production of shaded cocoa (Table 8). Although accounting for only 21% of the cocoa area harvested, the full sun production system is estimated to have accounted for nearly a third of recent output.

The extensive shaded scenario assumes that all full sun cocoa is reforested and converted to shaded cocoa through natural regrowth of locally occurring species. The conversion of 1 million ha of full sun to extensive shaded cocoa is assumed to reduce yields by 333 kg ha^{-1} on average. This results in a shortfall of 333,000 tons, requiring the degradation of an additional 764,000 ha of forest land for extensive shaded cocoa in order to maintain output at 2.65 M t (Table 8).

In contrast to the above scenario, the replacement of the extensive production systems currently characterizing most cocoa production in West Africa with intensified cocoa production systems would have resulted in considerable land saving (Table 8). Of the two intensification scenarios

Table 8 A comparison of the area and cocoa output by land use systems and production scenario in Cote d'Ivoire, Ghana, Nigeria and Cameroon

Scenario/land use system	Proportion of total land use (%)	Cocoa production by land use (000 t)	Area in land use (000 ha)
2007 Baseline			
Full sun cocoa	6	835	1,054
Shaded cocoa	24	1,816	3,957
Dense forest	69	0	11,340
Total	100	2,651	16,351
Extensive shaded (ES)			
Shaded cocoa	45	2,651	5,775
Dense forest	55	0	10,576
Total	100	2,651	16,351
Intensified full sun and cocoa-timber (IFS & CT)			
Intensive full sun cocoa	4	751	609
Intensive cocoa-timber	14	1,900	2,291
Dense forest	82	0	13,451
Total	100	2,651	16,351
Intensified cocoa-timber (ICT)			
Intensive cocoa-timber	20	2,651	3,197
Dense forest	80	0	13,154
Total	100	2,651	16,351

considered, the most land was spared by the mix of intensified full sun and intensified cocoa timber agroforests. The development of these intensified systems would have required the application of 1.08 million tons of fertilizer annually but doing so would have spared over 2.1 million ha of forest. If the intensified cocoa-timber system had been exclusively promoted, an estimated 1.19 million tons of fertilizer would have spared over 1.8 million ha of tropical forest.

Comparison of Forest Carbon Stocks and Emissions

The aggregate time-averaged carbon stock for each production scenario is estimated using the mean levels of carbon stock per ha for the three land uses considered, i.e. full sun cocoa, shaded cocoa and forest. The shaded cocoa scenario which is the most extensive system in terms of cocoa area would decrease total carbon stocks in the GRF relative to the 2007 baseline scenario by an estimated 90 million t of C (Fig. 3). In other words the development of the full sun production system even at its current extensive level of application has contributed to an increase of 2.53% in the combined carbon stock of cocoa systems and the dense forest in the GRF The land savings of the intensification scenarios, *ICT* and *IFS & CT*, would have resulted in even greater carbon sequestration through avoided deforestation and degradation with the gain representing a 12.5 and 13.3% increase in the total C stock of cocoa and forest land use systems in the GRF (Fig. 3).

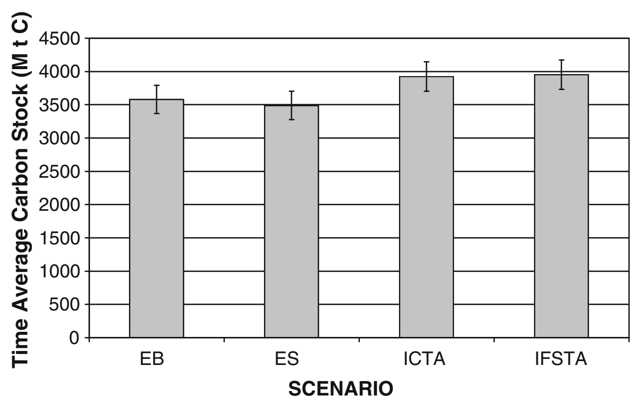

Fig. 3 Above-ground carbon stocks in extensive baseline (EB), extensive shaded (ES), intensified cocoa-timber (ICT), intensified full sun and intensified cocoa timber (IFS & CT) scenarios

Economic Returns of Extant and Alternative Cocoa Production Technologies

Partial budget and sensitivity analysis are employed to evaluate the average returns to the different cropping systems on a per ha basis under three price policy regimes. For the extensive full sun and shaded cocoa systems, all the labor is assumed to be supplied by the household and as such the gross margin is simply the cocoa yield per ha multiplied by the cocoa price. For the intensified full sun cocoa system, the gross margin per ha is calculated as (cocoa yield × price) − (fertilizer price × fertilizer quantity per ha). For the intensified cocoa timber system, the average annual gross margin is calculated as (cocoa yield × price) + (timber yield × stumpage price)/25 − (fertilizer price × fertilizer quantity per ha).

The cocoa-timber system is assumed to consist of a mixed association of cocoa and native timber species (*Terminalia superba*, *Milicia excelsa* and *Tieghemella heckelii*) with the timber species planted at a density of 50 trees ha^{-1}. Based on an extrapolation of allometric measurements of such systems in Ghana, 10 and 12 years after planting (IITA unpublished data), the timber crop is expected to yield on average 130 m^3 ha^{-1} of roundwood at the end of a 25 year cycle with a stumpage value of $100 per cubic meter when sold to local logging companies.

A comparison of returns reveals the preeminent position of the intensified systems regardless the price policy regime. Maximum returns occurred when the prices of both cocoa and fertilizer reached their market clearing equilibrium level under price policy regime #2 (Table 9). The intensified full sun system has a 148% to 161% higher return than the extensive shaded system depending on the price policy regime. Similarly, the intensified cocoa-timber agroforest has between 98 and 127% high returns.

The timber component of the intensified cocoa-timber system would account for 19% of the farmers' gross margin. The annual volume of timber that would have been generated is estimated at 16.6 and 11.9 M m^3 per annum under the *ICT* and *IFS & CT* scenarios. These quantities are relatively substantial. By comparison, average annual industrial roundwood production in the four countries from natural forests averaged 14.2 M m^3 from 2005 to 2007 (FAOSTAT).

The price policy regimes assume different rates of taxation and subsidy on cocoa and fertilizer inputs. Under the first regime the producer price of cocoa and the assumed tax are weighted averages from across the region from 2009/2010. The price used for regime #1 is actually above the price paid to farmers in Ghana and Côte d'Ivoire where taxation is relatively high and is below the price paid in Cameroon and Nigeria where taxation is low. The fertilizer price and subsidy reflect those prevailing in Ghana during the 2009/2010 production season. Under policy regime 1 (74% fertilizer subsidy) and regime 3 (50% fertilizer subsidy), the fertilizer subsidy costs would average 630 and 430 million USD per annum, respectively.

The Value of REDD Carbon in the Cocoa Sector of West Africa

Another potential economic value of the intensified systems would have been the value of avoiding emissions from up to 2.1 million ha of forest that would not have been required had "*fertilizer for forest*" intensification scenarios been successfully implemented. The net carbon emission per ha for shaded and full sun cocoa was calculated as the difference in the time-averaged carbon stock of the original closed canopy tall forest and that of the cocoa land use system. The difference was then multiplied by the area in that cocoa land use system and summed over land use systems to arrive at the estimated total carbon emission for the four production scenarios (Table 10). This value was then divided by the cocoa tonnage to arrive at the tons of C emitted per ton of cocoa. The 2009 mean price of $1.20 per t CO_2e from the voluntary market (Hamilton and others 2010) was used to calculate the estimated value of the 2007 baseline carbon emissions and the hypothetical value of avoided emissions due to intensification (with respect to the 2007 baseline). The value of the emissions that would have been avoided had alternative scenarios occurred is represented by Fig. 4.

Discussion

The expansion of low input extensive agriculture was identified as the principal cause of deforestation and forest degradation in the GRF with the cocoa, cassava, oil palm and plantain subsectors responsible for the greatest portion of land use change over the last 25 years. Cocoa production

Table 9 Estimated gross margins per ha for cocoa production systems under three price policy regimes

Cropping system	Price policy regime		
	#1 (tax and fertilizer subsidy) USD $/ha	#2 (no tax or subsidy)	#3 (reduced tax and subsidy)
Extensive shade cocoa	955	1,377	1,148
Extensive full sun cocoa	1,647	2,376	1,980
Intensive cocoa timber agroforest	2,169	2,726	2,452
Intensive full sun cocoa	2,490	3,420	2,944

Regime 1 cocoa price = $2.08/kg, cocoa tax = $0.92/kg, fertilizer price = $200/t, fertilizer subsidy = $560/t; *Regime 2* cocoa price = $3.00/kg, cocoa tax = $0/kg, fertilizer price = $760/t, fertilizer subsidy = $0/t; *Regime 3* cocoa price = $2.50/kg, cocoa tax = $0.50/kg, fertilizer price = $380/t, fertilizer subsidy = $380/t

Table 10 Estimated total C emissions by production scenario, C emissions per ton of cocoa produced and estimated global cost of GRF emissions by production scenario in Cote d'Ivoire, Ghana, Nigeria and Cameroon

Production scenario	Total carbon emissions (M t C)	Carbon emissions per unit of cocoa produced (Mg C per Mg cocoa)	Global Cost of carbon emissions[a] ($USD millions)
2007 Baseline	884	334	3,891
Extensive shaded (ES)	975	368	4,288
Intensified full sun and cocoa-timber (IFS & CT)	540	204	2,251
Intensified cocoa-timber (ICT)	512	193	2,374

[a] Cost of emissions evaluated at the 2009 price of $1.20 per t of CO_2e traded on the voluntary market

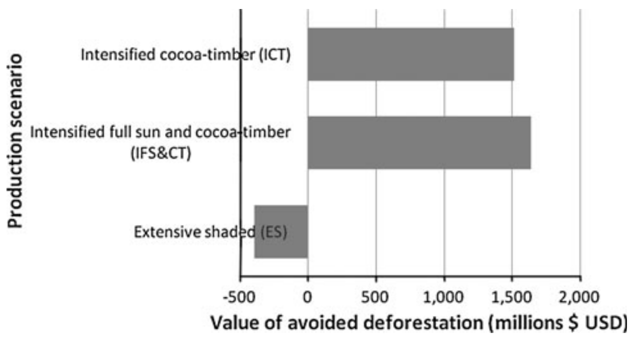

Fig. 4 Estimated value of carbon emissions that would have been avoided (relative to baseline situation) had alternative production scenarios been successfully pursued in Cote d'Ivoire, Ghana, Nigeria and Cameroon

in West Africa doubled from 1988 to 2007 as annual output expanded by over 1.4 M t. Most of this increase was fueled by the conversion of forests in areas of high conservation value with a high price paid in terms of biodiversity loss and carbon emissions.

The counterfactual analysis of cocoa intensification scenarios suggests that the expansion in output could have been feasibly achieved with little or no increase in the area harvested through increased applications of fertilizers and agrochemicals. Results showed that doing so would have increased farmer returns per ha by 98–160% above their current levels, would have avoided deforestation and degradation on over 2.1 million ha and in the process would have generated a value of over $1,600 million dollars on 1.366 billion tons of CO_2 emissions that would have been avoided.

The counterfactual analysis leads to the conclusion that agricultural intensification should be a principal component of so called REDD strategies in the seven countries that comprise the GRF. Instead of considering complicated strategies involving monetary or in-kind transfers to farmers or communities for altering their land use behavior, REDD funds could be used to incentivize and promote agricultural intensification efforts that would lead to higher rural incomes, greater food security, and avoided emissions through the achievement of higher agricultural yields.

Underlying the scenario analysis is the working hypothesis that productivity gains spare forests from land use conversion. This hypothesis, originally posited by Norman Borlaug, asserts that low land productivity is a fundamental driver of tropical deforestation and therefore efforts should be focused on increasing crop productivity in the tropical biome. The economic foundations of the hypothesis lie in the structural characteristics of agricultural markets, namely inelastic market demands combined with inelastic supplies of labor. The Borlaug hypothesis has been subjected to empirical testing and debate (Angelson and Kaimowitz 2001). Evidence in support of the hypothesis at a global scale has been presented by Waggoner (1994), Rudel (2001), Rudel and others (2009), and most recently by Burney and others (2010) who show that the increased GHG emissions associated with intensified agriculture and increased fertilizer use are greatly exceeded by reductions in emissions from the avoided deforestation that intensification engenders. In a counterfactual analysis, Burney and others estimated that the current global atmospheric stock of CO_2e would have been 34% greater were it not for the land saving, yield increasing agricultural innovations of the last five decades.

Green and others (2005) developed a theoretical framework for answering the question of whether it is better to encourage "wildlife friendly" agro-ecosystems or "land saving" agro-ecosystems for the conservation of a particular threatened species. When Indonesian primary forest was converted to cocoa agroforest, a 60% decline in vascular plant species richness was noted. However within a gradient of shade canopies, farm incomes were doubled when the canopy was reduced from 80% to between 35 and 50% while biodiversity and ecosystem functioning experienced only limited losses (Steffan-Dewenter 2007). The convexity of the biodiversity-yield tradeoff within varying levels of agroforestry intensification suggests that the opportunity cost of maintaining these ecological services may not be that high, particularly if the biodiversity value of the upper canopy can be combined with an economic value as for instance the proposed cocoa-timber associations.

The intensified system of cocoa planted in association with indigenous timber species has been proposed as a principal target for intensification efforts in order to help farmers meet their income objectives while contributing to higher biodiversity in the forest-agriculture mosaic that now characterizes the GRF. The largest portion of environmental benefits from intensified production systems scenarios would be achieved through the forest land spared from the chainsaw.

Taking pressure off the remaining remnants of the GRF is a critical objective. At present, nearly all the major protected areas of the GRF are under pressure from cocoa expansion including the Bia National Park/Resource Reserve and Krokosua Hills Forest Reserve in Ghana, Taï National Park in Côte d'Ivoire, Cross Rivers National Park in SE Nigeria, and Korup National Park and the Dja Biosphere Reserve in Cameroon (Oates and others 2000; Oates 2006). In Ghana, these protected areas provide some of the last remaining habitat for two of the 25 most endangered primates listed by the IUCN—the Roloway Guenon (*Cercopithecus diana roloway*) and the White-Naped Mangabey (*Cercocebus atys lunulatus*) (Oates 2006). Similarly the Cross-Rivers National Park in Nigeria is the westernmost range of the Lowland Gorilla. While Taï National Park in western Côte d'Ivoire is the single-largest tract of undisturbed tropical rainforest in West Africa and ranks among the highest priority tropical moist forest areas in Africa (WWF 2006). Tai is the last refuge in Côte d'Ivoire for keystone forest species such as the Forest Elephant (*Loxodonta africana cyclotis*), and the Pygmy Hippo (*Hexaprotodon liberiensis*).

While the major biodiversity benefit of intensified cocoa production occurs through land savings, the ecological benefits from including indigenous timber species at a broad scale may also be non-negligible (Norris and others 2010). Around the Dja Reserve, which is the largest protected area in Cameroon, there is gathering evidence of the importance of the biologically diverse cocoa forests surrounding the reserve as a seasonal food resource for large hornbills in the genus *Ceratogymna* (Tom Smith, pers. comm.). Field studies suggest that the black-casqued hornbill, *C. atrata*, and the white-thighed hornbill, *C. cylindricus albotibialis*, are involved in the seed dispersion of at least 56 species of trees and lianas in this area (Whitney and Smith 1998). The use of indigenous tree species as an ecological management tool to foster beneficial functions such as seed dispersal can be important, but unless the farmer is a fancier of hornbills, she may choose not to encourage such biodiversity especially if it comes at the expense of lower cocoa output. This is where ecological certification and payment for environmental services may have a role to play in incentivizing appropriate land use change.

Achieving the yield increases discussed in the intensification scenarios requires substituting fertilizers for forest biomass. This in turn assumes the existence of supporting market institutions and market infrastructure as well as supportive policies, research, extension, and roads. Significant public and private investments will both be required if the fertilizer sector is to achieve the level of impact envisaged in the intensification scenarios above, where the cocoa sector alone would annually require an estimated 1.2 M t of fertilizer to achieve the modeled outcomes.

Needed public investments include support for soil fertility research and extension. Also, given the positive externalities (i.e. avoided deforestation) associated with intensification, consideration should be given to fertilizer subsidies and tax incentives to encourage investment in fertilizer production and distribution capacity by the private sector. Significant economies of scale in fertilizer production suggest that initially private sector investments should focus on the development of the internal marketing capacity, i.e., bulk blending facilities and upcountry warehousing and distribution. Public investments to upgrade the facilities of West African ports to service large mega-container ships and to improve road infrastructure are needed to lower very high fertilizer marketing costs (Pálsson and others 2007).

Within the GRF, the private sector currently marketing the West African cocoa crop has made substantial investment in infrastructure for storing, transporting and exporting the 2.6 M t of cocoa produced annually. This infrastructure could well serve the importation and distribution of fertilizers for cocoa as well as other commodities.

Financial intermediation will also be fundamental for the success of a "fertilizers for forest" mitigation program to alleviate credit constraints that afflict both small producers and agro-chemical dealers along the supply chain. Production credit linked to cocoa markets is already occurring in Cameroon and Nigeria cocoa communities through cocoa exporters who have developed credit arrangements for fungicides and insecticides that are linked to output sales administered by their networks of village-based purchasing clerks. Gockowski and others (2009) estimated that approximately 50% of the cocoa producers in Nigeria and in the South West Province of Cameroon receive production credit to purchase inputs through these arrangements. Similar linked credit arrangements could be developed for the widespread promulgation of fertilizers as a first step towards the development of full financial intermediation.

Missing land markets are a major impediment to the efficient allocation of resources and the development of formal financial services. Land tenure reforms and promotion of cadastral surveys are needed to allow the development of formal land markets. There is also a need to develop improved seed and planting material production and distribution systems, markets for appropriate agricultural machinery and research on sustainable intensification practices in concert with outreach and extension activities.

The cocoa-timber associations proposed would require substantial changes in institutions and policies in support of on-farm timber production. Historically forest policies have not accorded timber rights for smallholder's planted timber, although this is beginning to change, regulatory systems and procedures for formally according those rights are often lacking. The scenario analysis suggests that intensified cocoa-timber systems could contribute significantly to future timber supplies. However, over the last 50 years, cocoa research has been mainly focused on the development of intensified full sun hybrid systems with fertilizers, with very little research done to support the type of intensified cocoa-timber system proposed. From the CRIG trials and the field survey, it is clear that shade reduces cocoa yields. What is less clear is whether or not the secondary output of these systems can adequately compensate for the decline in cocoa yields. Preliminary results suggest that they could, but there are uncertainties surrounding the production side and with timber marketing institutions. At present most timber produced on-farm in the GRF is processed by clandestine chainsaw crews who pay low stumpage prices in part because of the various bribes that must be paid to get their product into the internal market. In addition to the heavy informal taxes incurred in this supply chain, the wide kerf of a chainsaw is hardly the most efficient for transforming valuable tropical hardwoods into sawn wood. To assure the market, contractual arrangements and partnership with private logging companies may be necessary to convince producers of the viability of commercially oriented intensified cocoa-timber enterprises. Good timber management practices need to be validated and incorporated into extension programs. There is also remaining uncertainty about cocoa responsiveness to fertilizer application under shade. From the Ghana field survey, there was no difference in the fertilizer use frequency by type of production system and producers with shaded systems actually applied a higher fertilizer rate per ha than did producers with full sun systems although the difference was not statistically significant. Ahenkorah and others (1987) in Ghana found a significant response to fertilizers for shaded systems although the response was muted in comparison to the response of full sun systems. More agronomic research is needed on these systems to understand and optimize their response to soil amendments.

Although the cocoa sector has been analyzed in depth, we saw in the trends analysis that other commodities such as cassava and oil palm are characterized by similar extensive growth patterns. The activities and actions of a "fertilizer for forests" mitigation program with the emphasis on soil fertility and improved varieties has wide applicability for cassava and oil palm although underdeveloped road and market infrastructure may limit the spatial extent of market-driven intensification. The inclusion of these commodities in a sector-wide strategy for agricultural intensification and commercialization in the GFR would provide greater scope for private sector investment in the agricultural inputs sector that is fundamental to agricultural modernization in the GRF.

Concluding Remarks

The limited use of fertilizer in the GRF (less than 4 kg of total nutrients per ha) may have been logical in 1960, when West African populations were only 25% of today's levels and forest land was still relatively abundant. That choice is no longer tenable in a context where only 15–20% of the GRF remains and populations have trebled in size. There are no longer any frontier forests in West Africa for future generations to exploit. Strategies to reduce deforestation and conserve biodiversity in West Africa must focus on transforming agricultural practices from traditional to modern science based methods. "Fertilizers for forest" technology to sustainably intensify production is available and has achieved impressive yield increases on a limited scale in parts of the GRF. However delivering this technology and knowledge to West African smallholders will require overcoming many challenges. Credit constraints, an underdeveloped agro-chemical/fertilizer sector, inadequate seed multiplication, poor roads, and weak extension institutions all limit the capacity of smallholders to adopt innovations which have been on-the-shelf for the last 30 years.

Funding support for reducing carbon emissions due to deforestation and degradation (REDD) to mitigate climate change as discussed in the Copenhagen Accord offers the potential of significant new public resources for needed investments in agricultural research and extension and market infrastructure to support the transformation of traditional agriculture in West Africa. On a per ha basis, the estimated value of avoided CO_2 emissions are conservatively estimated at $565 for achieving the envisaged doubling of yields. A significant proportion of REDD + funding should be used to increase the adoption and level of fertilizer use in a "*fertilizers for forest*" mitigation program.

There is a risk that REDD interventions become captured by the forestry sector and neglect extensive low input agriculture which is the fundamental driver of deforestation in the GRF. In contrast to administratively complex PES schemes and reforestation/afforestation carbon projects, which have not yet been piloted in the GRF, functional research and extension institutions already exist and there is knowledge on how they could be rapidly strengthened. Doing so would directly address the fundamental driver of deforestation in sub-Saharan Africa.

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