Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis

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Abstract The change in stored carbon (C) stocks was assessed for a 700 km^2 area where forest cover decreased from 60% to 10% in the last 30 years. At the same time, the area under coffee increased from 7% to 70% with a gradual evolution from open "sun coffee" systems to multi-strata "shade coffee" systems that provide a partial compensation for C loss. The use of a generic tropical forest rather than tree-specific allometric equation can lead to substantial (up to 100%) overestimates of aboveground biomass depending on wood density and tree shape. The shoot:root ratio (biomass) of coffee shifted with age, from the 4:1 value often assumed for tropical trees to 2:1. Annual aboveground C stock accumulation rates during the establishment stage after slash-and-burn land clearing were 1, close to 2 or 3.5 Mg C ha^{-1}a^{-1} for sun coffee, shade coffee and fallow regrowth, respectively. Forest remnants, shade coffee and sun coffee had soil C stocks in the upper 30 cm of the soil that were 79%, 60% or 45%, respectively, of the values expected for primary forest in Sumatra. Total C stock (time averaged, above – 0.3 m in the soil) for forest, shade and sun coffee was 262, 82 and 52 Mg C ha^{-1}, respectively. In the 1970—1984 period, while forest cover was reduced from 59.5% to 19.7%, the landscape lost on average 6.8 Mg C ha^{-1} a^{-1}. In the 1984—2000 period forest cover was further reduced to 12.6%, but the landscape lost only 0.39 Mg C ha^{-1} a^{-1}, as forest loss was partially compensated by an increase in shade coffee systems. Conversion of all current sun coffee to shade coffee systems while protecting the remaining forest, could increase average landscape level C stocks by 10 Mg ha^{-1} over a time frame of say 20 years, or 0.5 Mg C ha^{-1} a^{-1}.

Keywords: allometrics, carbon stock, coffee, soil carbon, wood density.

Changes in carbon (C) storage in terrestrial ecosystems as a consequence of human land use have been simplified in the Kyoto protocol to a forest-nonforest dichotomy[1], and its derivatives (deforestation, reforestation, afforestation). As most definitions of "forest" depend on a threshold land cover fraction by woody perennials, the derived systems such as coffee plantations with or without shade trees may fall under the definition. The variation in C stocks within the forest category, whatever operational definition one chooses, is considerable and most of the changes due to a gradual degradation or aggradation of C stocks can remain unnoticed if one uses only two land cover classes. A more refined C accounting system is clearly needed to clarify changes in terrestrial C storage, and preferably the one that includes all land cover types, whether natural or man-made. Conversion of natural forest to smallholder farms can be dominated by tree crops: in Indonesia most of the rubber and coffee is produced by smallholders, who generally do not follow a monocultural plantation system. In fact, coffee can be the start of a complex multistrata agroforest[2] such as the damar (*Shorea javanica*) gardens of Krui, W. Lampung, where "shade trees" become a dominant feature of the vegetation and major source of income through the resin that can be harvested from them. In other coffee-based systems fruit trees and/or timber trees provide income in addition to the coffee and provide farmers with flexibility in maintaining income despite the boom-or-bust cycles of the world market for coffee.

Apart from the direct value[3] that soil and aboveground C stocks in shade coffee systems have for the farmer, increased terrestrial C storage is now seen as an "environmental service function" that slow the increase of greenhouse accumulation and its associated climate change. The providers of this function, that is the managers of land resources, including farmers, are not currently linked to the beneficiaries, especially the countries or their citizens with the highest C emissions due to fossil fuel use and the moral and contractual obligation to reduce net emissions. Mechanisms to provide such a link can take the form of "projects", with a clearly delineated area, time frame and set of responsibilities, or that of a more generic "program" for a larger area (e.g. a province or other part of a national administrative system) with accounting of changes in total C stocks. While the current emphasis is still on "projects", the level of control needed to guard against "leakage" (negative effects on C stocks elsewhere) and the concerns for "additionality" (only covering costs beyond what would make sense from a private profitability perspective) lead to high transaction costs and tensions between the outside entities and local administrative units[4]. In the longer term improved national C accounting systems may allow a more efficient "programmatic" approach to be followed, with C credits derived from actual changes in national C stocks. The accuracy of IPCC national C inventory schemes in Asia, however, is limited by uncertainties in the changes in areas under various types of land cover, as well as in the appropriate "activity" data, or typical C stocks to be assigned to the various land cover types[5,6].

The alternatives-to-slash-and-burn program has developed a protocol for assessing the above- and belowground C stocks of tropical land use systems that has been applied in the three main tropical continents[7—10]. The assessment includes trees, using allometric biomass equations, understorey vegetation, litter layer and soil C stocks in a nested sampling approach, to evaluate total C stocks in sample plots. Data on sample plots in different stages of the life cycle of a land use system are then used to derive a "time-averaged" C stock for the land use system, that in combination with area-based data on land use change can lead to estimates of changes in terrestrial C stocks for a well-defined area over a specified period of time. Uncertainties in the estimates originate at the various steps between field level observations in sample plots and the final total C stock calculation[6].

Generic equations for mixed tropical forests in different climatic domains[11] may not be valid in view of the differences in wood density between primary and secondary forests[12]. An equation[13,14] that includes wood density and a parameter from the relationship between tree height and stem diameter may be more reliable. A method for estimating allometric equations on the basis of fractal branching rules uses tree-specific parameters that can be obtained non-destructively, for root systems (belowground trees) as well as aboveground[15]. For pruned coffee trees adjustment for the modified diameter-height relationship is probably needed, while bamboo, palms and bananas require specific equations.

Soil organic matter can play a positive role in crop production and as such the interests of farmers and external stakeholders in maintaining high soil C stocks can coincide. For the various coffee systems for acid soils in the humid tropics an initial assessment of the direct benefit of soil C can focus on its assumed role in mitigating the effects of acidity and aluminium toxicity[16].

In the research reported here, we set out to quantify the field-level changes in the above- and belowground C stocks of a conversion of forest to “sun” or “shade” coffee systems, the historical landscape level changes in C stocks for a benchmark area and scenarios that may lead to a partial recovery.

1 Materials and methods

1.1 Study area

Measurements were made in the Sumber-Jaya subdistrict (104° 19′—104° 34′E, 4° 55′—5° 10′S; 780—1700 m a.s.l.; mean rainfall 2500 mm a^{-1}; W. Lampung, Sumatra, Indonesia) that approximately equals the catchment area of the Way Besai, one of the main tributaries to the Tulang Bawang river that flows east through the lowland peneplain. The Way Besai flows almost full circle around the Bukit Rigis (1623 m a.s.l.) in the center of the catchment, with its top still covered with forest; and other forest remnants left intact on the steeper outer edges of the catchment area. The major soils are inceptisols (Dystropepts, Dystrandepts and Humitropepts) with some entisols (Troporthent). The area has a long history of human use, as evidenced by the 8th—11th century megalithic remains in the area with Chinese ceramics indicating long distance trade relations[17]. Human population density was low till about 1900[18], when the area was settled by Semendo migrants from S. Sumatra Province followed by Javanese and Sundanese in the 1950s and 1970s.

1.2 Plot-level C stocks

In a first survey 24 plots were sampled in Sumber-Jaya in September 1999, including the remnant forests on the ridge top, multi-strata “shade coffee” gardens (2, 8, 10, 20 and 30 years after slash-and-burn land clearing), monoculture “sun coffee” (1, 2, 8, 9, 20, 21 years old) and fallow (1 and 20 years old). In each plot the diameter and height of live and dead trees were measured in 40 × 5 m^2 plots with litter and understorey samples in subplots (for full protocol see ref. [10]). A full description of this survey, including botanical composition of the plots will be published elsewhere[19]. In a second survey the composition of 19 multi-strata “shade coffee” plots was described.

1.3 Trees

Tree biomass (W, dry weight) was estimated using the allometric equation on the basis of stem diameter at 1.3 m above the ground (D)[13]:

$$W = 0.11\,\rho D^{\,2+c},$$

where ρ is the wood density and the coefficient c is based on the allometric relation between tree height (H) and D : $H = aD^c$ (default value for $c = 0.62$).

For comparison, the generic allometric equation for humid tropical forests was used[11]: $W = 0.118D^{2.53}$.

To avoid the need for measuring wood density ρ for every individual tree, a database of literature values was developed, recording lower bound, upper bound and medium values. Currently the database holds entries for 2800 tree species and will be shortly made available via www.icraf.cgiar/sea. Wood density (at a standard 15% moisture content) can be classified as light (density less then 0.6 Mg m^{-3}), medium (between 0.6—0.75 Mg m^{-3}), heavy (0.75—0.9 Mg m^{-3}) and very heavy (more than 0.9 Mg m^{-3}).

For pruned coffee, bamboo and banana separate allometric equations were used, derived for similar conditions in East Java (fig. 1) as quoted in ref. [10]. For pruned coffee we used $W = 0.281D^{2.06}$, the power of which agrees with the equation of ref. [13], as $c = 0.08$ ($H = 1.79\,D^{0.08}$). For banana biomass based on pseudo-stem diameter we used $W = 0.030\,D^{2.13}$. For bamboo we used $0.131\,D^{2.28}$. Total C content was calculated from biomass assuming a C content (per unit dry weight) of 0.45.

1.4 Roots

Fractal branching models provide a transparent scheme for deriving tree-specific scaling rules on the basis of easily observable, non-destructive methods[15]. These models repeatedly apply the same rules (equations) to derive subsequent orders of the branching process. When a rule is added for stopping when a certain minimum size is reached, the total size of a branched root (or aboveground tree) can be derived on the basis of initial (proximal) root (stem) diameter. In a spreadsheet model (functional branch analysis, or FBA) available at www.cgiar.org/icraf/sea/agromodels/wanulcas/wanulcas.htm, the relations between five input parameters and the parameters of the allometric biomass equations a and b can be explored. Five parameters describe the branching process: n = average number of branch offspring per branching point, p = proportionality of stem cross sectional area before and after branching, q = allocation of offspring cross sectional area to the largest link, L_m = length of a link (internode) at minimum stem diameter and r = slope of the regression of link length on stem diameter.

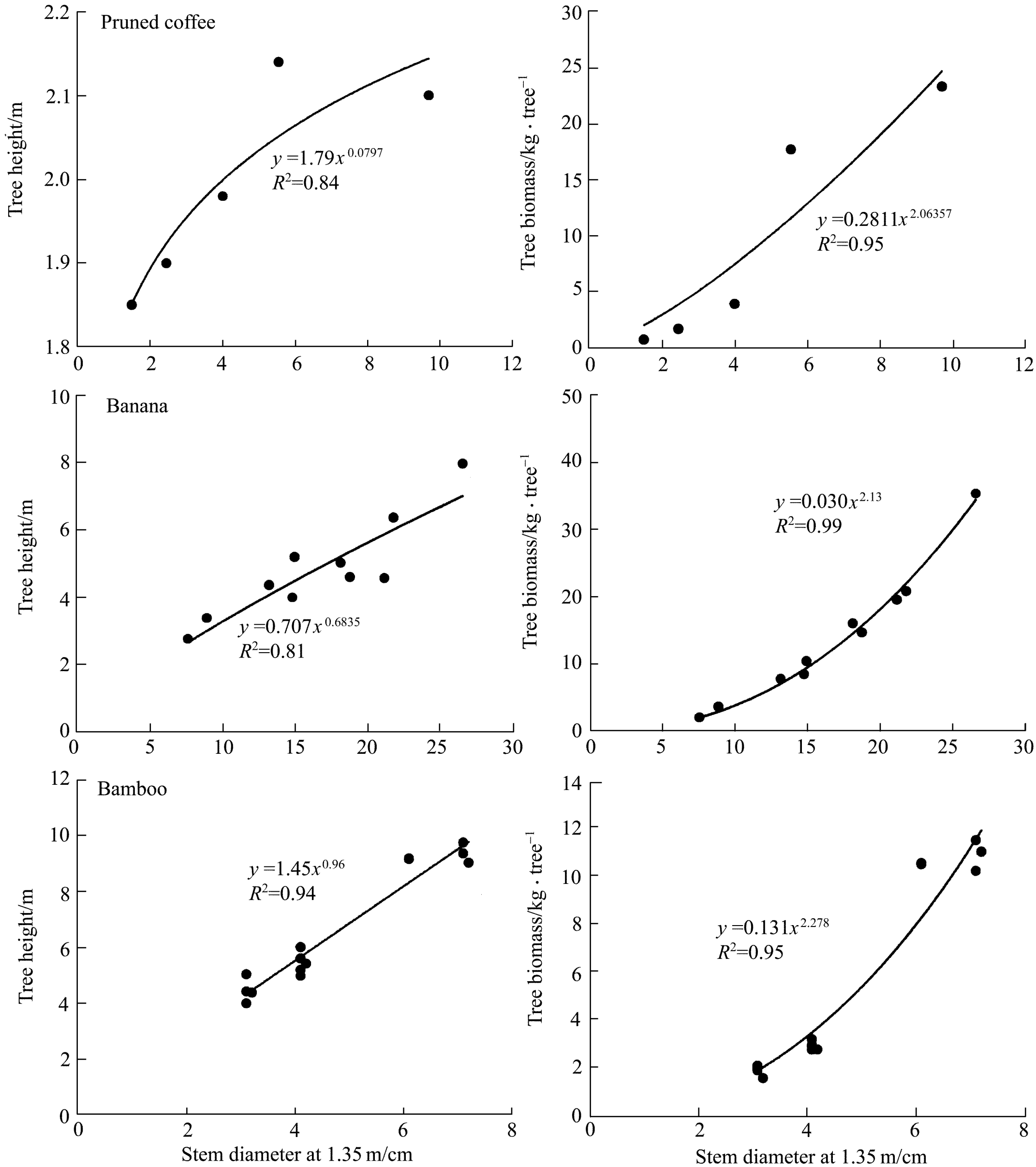

Fig. 1. Allometric relationships between (pseudo)stem diameter and plant height or biomass (dry weight) for pruned coffee[10].

Proximal roots were exposed on 3 coffee trees, with the age of 1, 3, 7 and 10 years, respectively and their diameter and orientation was recorded. A number of roots of 6 coffee plants were exposed and the parameters n, p, q, L_m and r were derived for a total of 34 branching points. With the FBA model[15], the following allometric equation was derived for coffee roots: $W = 0.0074\ D_{prox}^{3.14}$.

1.5 Soil carbon

For the 24 samples in the first land, cover survey soil samples of the 0—5, 5—15 and 15—30 cm depth layer were collected and analyzed for Corg (Walkey and Black), texture (sand, silt clay), pH (1 mol • L^{-1} KCl), exchangeable bases (Na, K, Ca and Mg), exchangeable Al and acidity.

A dimensionless "*C* saturation deficit", C_{satdef}, was calculated as the difference between the current C_{org} content and a reference content, $C_{org,\ ref}$ which is supposed to indicate the undisturbed forest condition:

$$C_{satdef} = (C_{org,\ ref} - C_{org})/C_{org,\ ref} = 1 - (C_{org}/C_{org,\ ref}).$$

The ratio[20] of measured C_{org} and a reference C_{org} value for forest (top) soils of the same texture and pH can serve as "sustainability indicator". The current version incorporates a generic C distribution with depth[10]. The equation for $C_{org,ref}$ for Sumatra is

$$C_{ref(adjusted)} = (Z_{sample}/ 7.5)^{-0.42} \exp(1.333 + 0.00994 \times \%Clay + 0.00699 \times \%Silt - 0.156 \times pH_{KCl} + 0.000427 \times Elevation + 0.834 \text{ (if soil is Andisol)} + 0.363 \text{ (for swamp forest on wetland soils)}.$$

The depth adjustment factors for the layers 0—5, 5—15 and 15—30 cm are 1.59, 0.89 and 0.63, respectively.

1.6 Time-averaged C stock

For the rotational land use systems, which include a clear felling at the start (or end) of every production cycle, a "time-averaged" C stock can be used for landscape scale assessments, as it reflects a "spatially averaged" value on the assumption of a steady rate of renewal[8]. For the coffee production systems in Sumber-Jaya, we can distinguish an establishment period of approximately 5 years from a mature phase in which continuous tree rejuvenation (by direct grafting of the coffee and gradual replacement of companion trees) causes fluctuations around an average value, without a clear felling phase.

1.7 Landscape-level change in C stock

Local land use maps[21] from 1970, 1978, 1984 and 1990 were complemented by June-2000 Landsat ETM imagery. For each of these years we calculated landscape-level C stock by multiplying areas per land use with the time-averaged C stock of the land use type.

2 Results and discussion

2.1 Biomass carbon

The median mid-range wood density for tree species found in the remnant and secondary forest was 0.61 Mg m^{-3} (with a distribution of species as follows: light 40.8%, medium 31.7%, heavy 15% and very heavy 12.5%) (fig. 2). The median mid-range wood density for tree species found in multi-strata coffee gardens was 0.75 Mg m^{-3} (light 39.2%, medium 38.5%, heavy 15.2% and very heavy 6.5%).

Compared to the "generic"[11] allometric equation, use of tree-specific allometrics that include estimates of wood density tends to lead to lower biomass estimates (fig. 3), especially in the low-to-medium biomass categories. As all earlier ASB results[8,9] used the generic[11] equation, some cautions are needed when comparing the results.

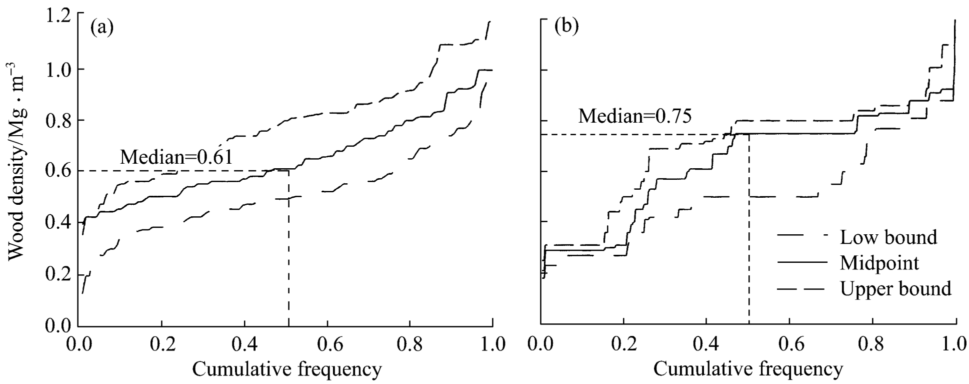

Fig. 2. Cumulative frequency of wood density estimates found in a broad-based literature survey. (a) A species list from the secondary forest in Sumber-Jaya; (b) a species list of the multistrata coffee gardens in Sumber-Jaya. These data are extracted from a wood density database that currently includes 3500 tree species, with a lower- and upper-bound estimate for most species, as well as a midpoint estimate for all; the database will be made available via ICRAF-SEA web-site.

Three remnant/secondary forests were included in the survey, with a mean estimated aboveground biomass of 390 Mg ha^{-1}. Only 8% of this amount derived from the litter, dead trees and undergrowth. For two fallow plots of 1 and 20 years after the last slash-and-burn land clearing, aboveground bio- and necromass was estimated to be 9 and 170 Mg ha^{-1}, respectively. The younger fallow did not contain woody biomass; for the older plot 10% of the total was derived from litter, dead trees and undergrowth. The total biomass average in shade coffee gardens from 2 to 30 years old was around 92 Mg ha^{-1}; 25% of this value derived from litter, dead trees and undergrowth. The total biomass average in monocultural sun coffee between 1 and 21 years old was 44 Mg ha^{-1}, 48% of which was litter, dead trees and undergrowth. The difference between shade and sun coffee was thus close to 50 Mg ha^{-1} of biomass, or 20 Mg ha^{-1} of aboveground C stock.

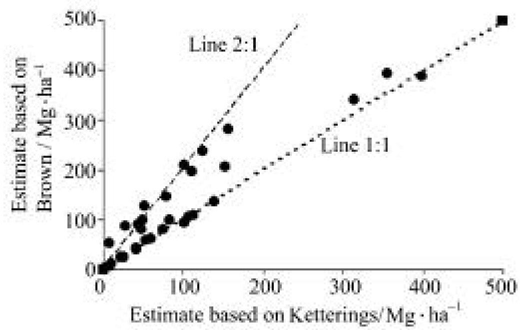

Fig. 3. Comparison of the aboveground biomass estimates based on the (generic tropical forest)[11] allometric equation and estimates based on the equation[13] that accounts for the wood density of the tree species (using the mid range estimates from a broad literature data review).

In the second survey, the average C stock in aboveground biomass of coffee trees in shade coffee gardens between 6 and 40 years of age was 18.4 Mg ha^{-1}, with a standard deviation of 4.0,

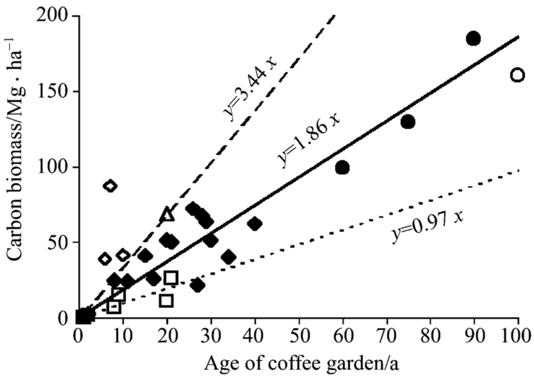

Fig. 4. Relationship between aboveground C stock and age of coffee gardens (presumably since last clear-felling or slash-and-burn land clearing, but note that for some of the shade coffee gardens the age of the coffee plants is used as X-axis as the age of the garden is unknown).◆Mixed; ◇mixed (incl. older trees); □ monoculture; △fallow; ○forest; ●damar.

and the average for non-coffee trees was 29.6 Mg ha^{-1} with standard deviation of 18.9. By plotting the total aboveground C stock data against the age of the garden (fig. 4, note there are some confusions between the age of garden and the age of coffee, indicating that not all coffee was planted after clear-felling), we can estimate the annual C stock increments as roughly 1 and 2 Mg C ha^{-1} a^{-1} for sun and shade coffee respectively. This is less than the inferred C accumulation rate for bush fallow here (although we do not have enough data points), or in previous data sets for Sumatra[8]. Three sample points for the damar agroforest of Krui (derived from data in ref. [2]) fit remarkably well to the extrapolated line for "shade coffee".

While the shoot∶root biomass ratios for tropical forests under normal upland conditions are normally in the neighbourhood of 4∶1, our data on coffee suggest a decrease of the shoot∶root ratio with the age to about 2∶1, for the regularly shoot-pruned coffee trees in Sumber-Jaya (fig. 5).

2.2 Soil C

Soil organic matter contents for the forest sites are in the range expected for Sumatra[20], once the soil texture and soil pH are taken into account in the Cref value and adjustments were made for sampling depth. The relative soil C content (C/C_{refadj}) was around 0.79 (0.82 for 0—5 cm, 0.84 for 5—15 cm and 0.71 for the 15—30 cm layers) in the forest sites, around 0.60 for the mixed coffee gardens (on average 0.58, 0.70 and 0.52 for the three soil layers, respectively) and 0.45 for monoculture coffee (0.43, 0.52 and 0.41, respectively). When plotted against the time since forest conversion (fig. 6), there is an indication of decline of the C/C_{ref} value with time in the coffee monocultures, and a possible recovery towards forest values in the mixed coffee gardens.

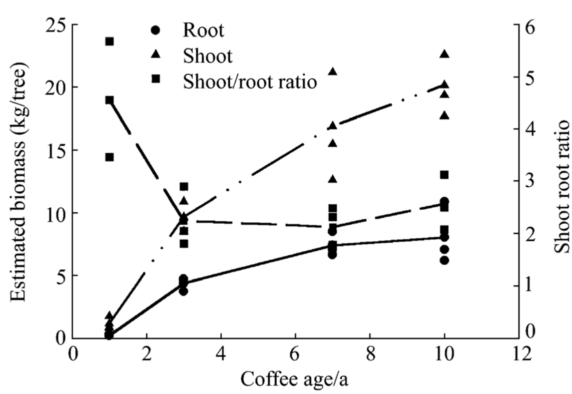

Fig. 5. Estimates of above- and belowground biomass of coffee and shoot∶root ratio, based on allometric equations for stem diameter (empirical equation) and proximal roots (derived from fractal branching model with parameters derived from coffee in Sumber-Jaya).

2.3 Time-averaged C stocks and landscape level changes

The data for soil C, root biomass and aboveground biomass of trees, necromass, litter layer and understorey or herb layer, were combined to derive time-averaged C stocks (above a soil depth of 0.3 m) for the first 25 years of sun and shade coffee of 52 and 82 Mg C ha^{-1}, which are considerably below that of the remnant forest (262 Mg C ha^{-1}) or the young secondary forest (remnant of "shifting cultivation"), at 96 Mg C ha^{-1}.

By multiplying the land area under the various land cover categories with the current estimates of time-averaged C stocks, we obtain estimates of landscape-level changes in C stocks (fig. 7). From a level of about 200 Mg C ha^{-1} in 1970 (59.5 % forest cover) the decrease was 6.8 Mg C ha^{-1} a^{-1} in the first 14 years to a value of 92 Mg C ha^{-1} in 1984 (19.7% forest cover). The further loss of forest cover in the period of 1984—2000 (till 12.6%) led to a landscape level loss of only 0.4 Mg C ha^{-1} a^{-1} to 86 Mg C ha^{-1} in 2000, as shade coffee systems replaced some of the sun coffee, while grassland as land cover category was reduced from 15.6% in 1984 to 9.9% in 2000.

Using the same data we can

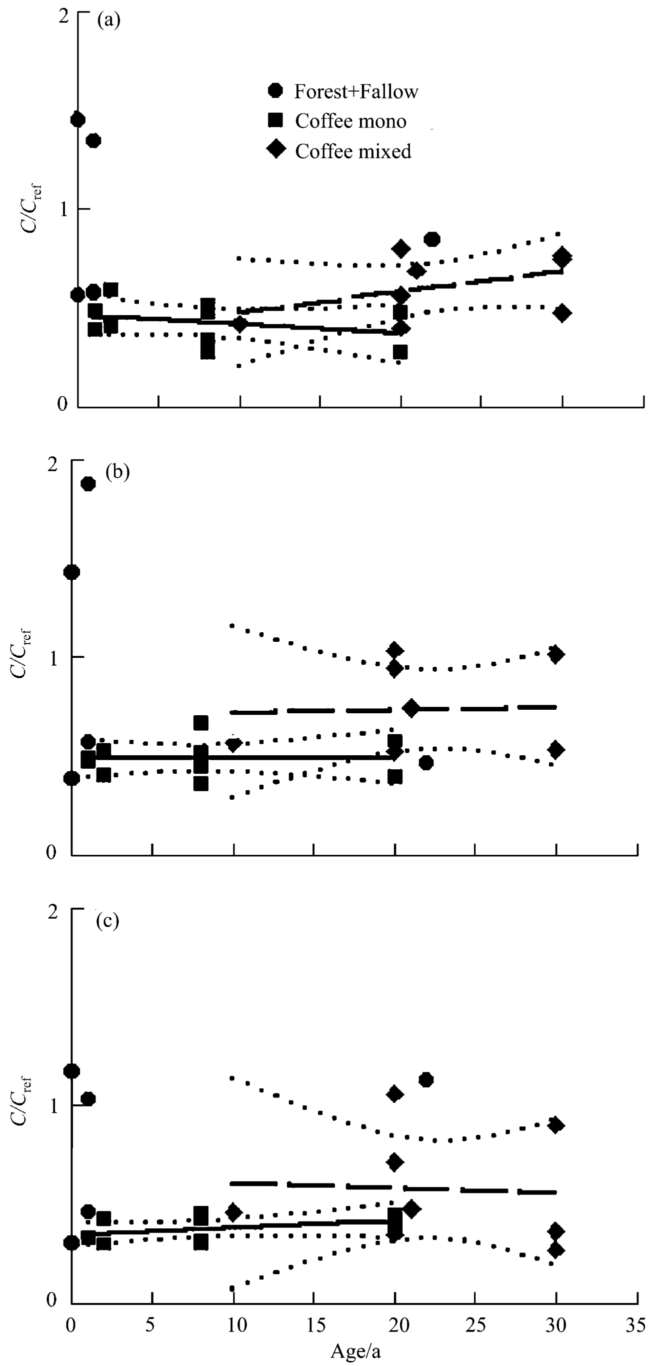

Fig. 6. Relationship between the C_{org} content of the soil relative to the reference value (C_{refadj}) as a function of age, for the open coffee monocultures and the mixed coffee systems, that include other trees; linear regression lines with 95% confidence intervals are drawn; for comparison three samples of damar agroforest[2] are added. (a) 0—5 cm in depth; (b) 5—15 cm in depth; 15—30 cm in depth.

explore a scenario where all currently open land and sun coffee systems are converted to shade coffee over the next, say, 25 years, while current forest cover is maintained. This may lead to a landscape level C stock of 102 Mg C ha^{-1}, which is 10 Mg C ha^{-1} above the 1990 value.

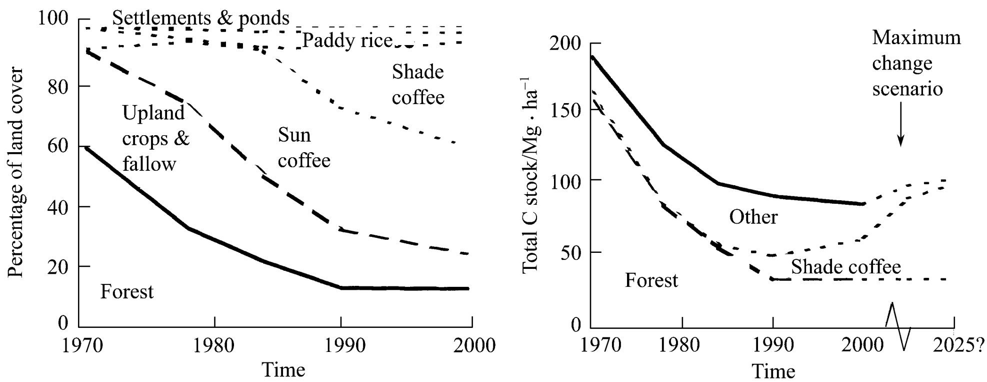

Fig. 7. Landscape level C stocks above a soil depth of 0.3 m for Sumber Jaya in the period of 1970—2000, with an extrapolation to the future assuming all coffee gardens to become "shade coffee", while the remaining forest is left intact.

2.4 Concluding remarks

The differences in C stocks between sun and shade coffee (about 30 Mg ha^{-1} in time-averaged C content) may appear relevant when valued at a current global C market price[4] of 8 \$ Mg^{-1} and a (discounted, private prices) net present value (NPV) of the coffee production systems[22] of 450—3250 \$ ha^{-1}. The lowest NPV reflects pioneer coffee monocultures with insecure land tenure and low management intensity, the highest ones complex coffee gardens with secure tenure and medium management intensity. These results were based on 1997 estimates of long term price averages, before the "monetary crisis"; at current prices the NPV might be only a third of this amount. Yet, the chances that smallholder coffee growers in Sumber-Jaya can directly capitalize on such a world market value for additionally stored C are slim. First of all, transaction costs for any marketing and certification may well exceed or come close to the supposed market value, unless substantial economies of scale can be achieved by grouping of smallholder producers[4]. Secondly, current data suggest that shade coffee systems, that maintain higher C stocks, are already more profitable than low-C stock sun coffee systems, so a transition from sun to shade coffee would not pass the "additionality" criterion. As the "leakage" aspect for any rewards on coffee systems that have recently been obtained by forest conversion is daunting, the only chance may be for larger units, for example the Sumber-Jaya sub-district of 700 km^2, to become the scale of analysis and C accounting. In that case an existing local administrative unit would become responsible for at least maintaining current landscape-level C stocks, with an option for increasing it with the said 10 Mg C ha^{-1} in the next decade(s), if overall incentives (e.g. tenurial and tax) favour shade coffee development. A further point to note is that although shade coffee systems as a category represent a "win win" solution for both private and external (environmental) interest groups when compared to "sun coffee", there may very well be negative trade-offs between C stocks and profitability within the "shade coffee" class of land use systems. A more detailed classification system would then be needed, along with more refined techniques for monitoring land use by remote sensing data. For the time being, the opportunities for C sequestration reward mechanisms are larger for smallholders in more C-depleted landscapes, as for example in the ASB N. Lampung benchmark area in the lower reaches of the Tulang Bawang river where deforestation has been completed and smallholders now start to re-plant trees in depleted landscapes[23,24].

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