Nearly half of the Andisols (43.2%) is used for permanent cropping (mostly tree crops). On the other soils permanent crops represent 13.5-19.8% of the data set, with the lowest value for the Oxi- and Ultisols and the highest for the wetland soils (mostly sawah).

The group indicated as S&B group consists of annual crops and two vegetation types which may be interpreted as fallow land: shrub and *Imperata* grasslands. This interpretation is only a first approximation, as some of the shrubland, esp. on the wetland soils may be natural. Figure 2.2.10 shows the relative composition of the S&B series on the three upland soil types. Crops are 14% of the S&B series on the Oxi- and Ultisols (indicating an overall crop: fallow ratio of 1:7, a very rough estimate), 21% on the alluvial upland group (tentative crop: fallow ratio 1:5) and 29% on the Andisols (1:3.5). This ratios correspond with a trend of increasing soil fertility from the Oxi- and Ultisols to the Andisols. Interestingly, on all soils the area under *Imperata* grasslands is equal to the area used for annual crops. The ratio of permanently cropped land and the S&B series is lowest on the Oxi- and Ultisols (1: 2), highest on the Andisols (2:1) and intermediate (1.2:1) on the other soil orders.

Figure 2.2.11 shows the average soil C content of the topsoil (about 15 cm) on vartious soil groups classified by land use in the late 1980's. Histosols obviously have the highest C_{org} content. Based on data of total profile C storage of Eswaran *et al.* (1993) we may expect that the Histosols, which cover 10% of Sumatra, contain more than 90% of all C stored in Sumatransoils. The Andisols and the wetland soils both contain about 10% of C_{org}. On the Andisols C is intimately bound to clay complexes, while in wetland soils, the C is partially protected from decomposition by anaerobic conditions. On the relatively fertile upland soils (Incepti+sols) and the Oxi- and Ultisols, the C_{org} content is 3.8 and 3.2%, respectively. The differences between all groups were statistically significant in a t-test. Within the groups presented, no statistically significant differences between soil types were observed.

The wetland soils include human-made wet rice fields. The C_{org} content of these managed wetlands was below that of their natural counterparts in the sedge swamps. The widespread practice of burning rice straw at the end of the cropping cycle and the relatively young age of these wetlands may limit the accumulation of soil organic matter compared to natural wetland vegetation.

In general, the C_{org} content decreases from primary forest, to secondary forest to areas used for tree crops and the S&B series. On the major upland soils, the difference in C_{org} content between land use types is about 0.5% C. At an average bulk density of 1.25 g cm^{-3}, this represents 10 Mg ha^{-1} for a 15 cm top soil layer. Changes in deeper layers may be expected to be less, and the total change is probably less than twice the change estimated form the top layer only. On the Andisols and the wetland soils, larger differences in C_{org} content are observed between land use types, but the smaller number of observations makes comparisons less certain. Potentially, land use effects on C_{org} may be more pronounced on these soils as management reduces the protection of C_{org} when Andisols are tilled and wetland soils drained. The clearest example of interactions between land use and soil type is the relatively low C_{org} content of perennial tree crops on Entisols; this is largely based on coconut plantations on sandy soils at low elevation.

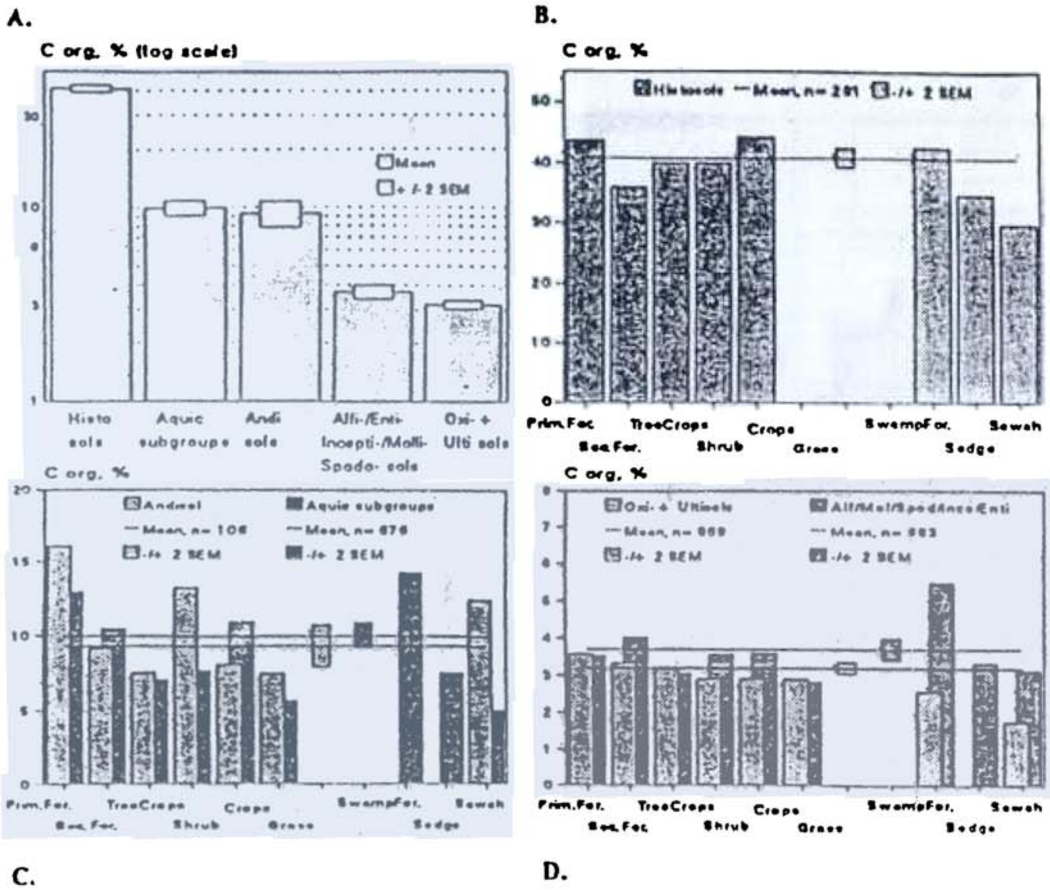

Figure 2.2.11. Average C_{org} content of the topsoil according to the soil database for Sumatra (Indonesia) of the Centre for Soil and Agroclimate Research, Bogor. A. Average per soil group (note logarithmic scale); B, C, D average values per land use category, the horizontal line indicates the averaghe per soil group, the error bar indicates plus and minus two times the standard error of the mean (SEM).

A comparison can be made with an analysis made in the 1930's of a large data set obtained by Hardon (1936) from Lampung on the southernmost corner of the island. Lampung was then under transformation from forest to agricultural land, a change which today has been virtually completed. For nearly all land use categories, Hardon's data fell within the more recent data for the Incepti+sols and the Oxi- and Ultisols. Hardon's average topsoil content over all land uses (3.53 %) is close to the present average of 3.46% for these soil groups. We conclude that the average C_{org} content of the topsoil in Lampung/S. Sumatra in the early 1930's was similar to the average for the whole of lowland Sumatra, excluding volcanic, wetland and peat soils in the late 1980's. There is no indication of any change in soil C storage under forests in the 50 year time

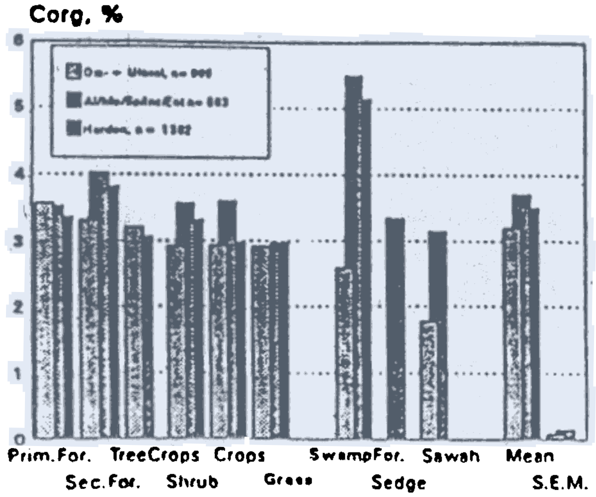

Figure 2.2.12. Comparison of C_{org} of topsoil in the 1980's, with a dataset for S. Sumatra from the 1930's (Hardon, 1936).

span during which atmospheric CO_2 concentration increased by 20% in this period, from 0.29 to 0.35%.

Figure 2.2.13 shows the relation between soil pH and the average C_{org} content of the pH class. The data set for the 1980's confirms a relation established in the 1930's by Hardon (1936). No indication what so ever of a change in C_{org} is found over a 50 year period. The combined data show that the lowest C_{org} content can be expected in the pH range 5.0-6.0. Below a pH of 5.0 reduced biological activity may slow down the break down of organic matter. Interestingly, most agricultural research recommends lime applications to the range 5.0 - 6.0; this may stimulate breakdown of organic matter and thus contribute to crop nutrition, but possibly at the costs of maintaining the soil organic matter content. By selecting acid soil tolerant germplasm, adequate crop production can be obtained in the pH range 4.5 - 5.0, with higher C_{org} levels (this statement needs further corroboration).

A multiple linear regression analysis of C_{org} on pH, texture, altitude and slope resulted in heterogeneous regression residues (data not shown). The C_{org} data were log transformed and this resulted in more homogeneous residues. The resulting regression model is therefore multiplicative instead of additive. The multiple regression analysis (Table 2.2.4), includes soil pH, texture, altitude, slope, land use and soil type. All these factors were entered stepwise into the equation. The quantitative factors: pH, clay and silt, had a slope which differs significantly ($p<0.001$) from zero. The relative weighing factors for clay and silt are 1.4 and 1.0, respectively. The regression coefficient for altitude ($p<0.01$) and for slope ($p<0.05$) were also significant from zero. In this regression, the effects of altitude are studied separately from the

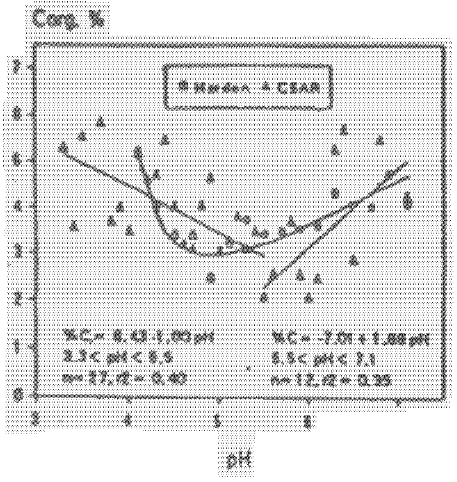

Figure 2.2.13. Relation between soil pH and organic carbon content of the topsoil in lowland (< 200 m) forests; data for the 1930's are indicated by squares (Hardon, 1936) and for the late 1980's by triangles; in both cases the average C_{org} content is given per class of soil pH (per 0.1 unit).

different altitudinal distribution of soil groups. They indicate a positive effect on C_{org} of lower temperatures. The effect of slope suggests that a low rate of erosion also is an *(in situ)* protection mechanisms for soil organic matter. The regression equation leads, for example, for an Inceptisol with pH 4.0, 25% Clay + 25% Silt, altitude 200 m a.s.l., slope 10% and under alang-alang:

$$C_{org} = \exp(+1.333 -0.0245 -0.624 +0.424 +0.085 -0.026 +0.011) = e^{1.179} = 3.25\%.$$

In the overall data set the upward trend of C_{org} at higher pH was not very pronounced, and adding a quadratic term (pH^2) did not significantly improve the percentage of variance accounted for by the regression equation. Compared to the average contents per soil type and land use, the C_{org} content will decrease 15% per unit increase in pH, increase 1% and 0.7 per percent increase in clay and silt content, respectively, increase by 4% per 100 m increase in altitude and decrease by 0.3% per percent increase in slope. A point of caution is needed, however, as a considerable part of the variation in the data set remained unexplained. This may indicate inadequacies in the classifications used, or the importance of factors not included in this study, such as the time period elapsed since a change in land use occurred.

No indication was obtained that tree-based production systems in plantations differ in C_{org} content from land used for annual crops. For research concerned with the global C budgets and the effects of land use change on C emissions, priority should be given to the peat and wetland soils; drainage of a few percent of the Histosols may release more CO_2 into the atmosphere from current soil sources than transformation of all remaining forest into *Imperata* grasslands. Evidence for a number of 'protection factors' could be obtained: waterlogging, low pH,

Table 2.2.4 Multiple linear regression of $\log(C_{org})$ for Sumatra soil database, derived by step function of Genstat V, with inratio=6 and outratio=6; a logarithmic transformation was used to obtain homogeneous residuals; only soils with complete texture data were included, Histosols were excluded for the analysis.

$\mathrm{Log}(C_{org})$ = 1.333 + 0 (if soil is Oxi- or Ultisol)
0.011^{NS} (if soil is Incepti+sol) +
0.834^{**} (if soil is Andisol) +
0.363^{**} (if soil is FluvAqsuborder) +
0.00994^{***} * Clay% + 0.00699^{**} * Silt% +
-0.156^{**} * pH +
0.000427^{**} * Altitude +
-0.00264^{*} * Slope +
+ 0 (if LU is Swamp forest) +
-0.077^{NS} (.. Primary forest) +
-0.082^{NS} (.. Secundary forest) +
-0.169^{NS} (.. Upl_crops) +
-0.245^{*} (.. Alang-alang) +
-0.267^{*} (.. Perennial crops) +
-0.288^{*} (.. Shrub) +
-0.335^{*} (.. Sedge) +
-0.433^{*} (.. Sawah)

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mineralogy (Andisols), texture, altitude (temperature) and slope all have a significant effect on the C_{org} content of the top soil.

In peat soils rapid changes can occur after drainage. C losses can lead to subsidence of the soil profile (which is difficult to measure in a landscape without fixed points of reference), changes in bulk density and decrease in C content of the remaining soil. Nugroho and Widodo (1993) tested 7 peat soils in as column experiment were soils were drained for 1 month and then irrigated for 2 months. The C_{org} content decreased from 55 to 40% on 4 soils derived from a shrub vegetation and from 55 to 50.5% for 3 soils derived from swamp forests on Sumatra and Kalimantan. This substantial decrease only reflects of the C losses, as soil shrinkage (subsidence) was not measured. Total C losses can be estimated if we assume that the mineral parts of the soil remain unchanged and express the measured C content per unit mineral soil, instead of per unit dry weight, assume total organic matter content to be 1.7 times C_{org}, and mineral parts to be 100% - soil organic matter content. If $C_{org,0}$ and $C_{org,1}$ indicate the C_{org} content before and after drainage, respectively, the C losses relative to the initial amount equal:

$$\textit{Relative C loss} = \frac{C_{before} - C_{after}}{C_{before}} = 1 - \frac{C_{org,1} \cdot (100 - 1.7 \cdot C_{org,0})}{C_{org,0} \cdot (100 - 1.7 \cdot C_{org,1})} \quad (1)$$

Applying this equation to the data of Nugroho and Widodo, we estimate the relative C losses in their experiment to be 85 and 60% of the initial stocks, respectively.

From this tentative evaluation of the CSAR soil data base a number of conclusions (or hypotheses for further research) can be formulated for the ASB project:

- slash-and-burn farming methods occur on all upland soil types in Sumatra,
- on the poorest soils (Oxi- and Ultisols) the lowest crop: fallow ratios were found within the tentative S&B series,
- the ratio of permanently cropped land and the S&B series is lowest on the Oxi- and Ultisols (1: 2), highest on the Andisols (2 : 1) and intermediate on the other soil orders,
- existing land use, including S&B, on the Oxi- and Ultisols may be the least sustainable; the need to replace it by more permanent production systems may be highest on these soils,
- only small areas of primary forest remain on any of the soil types; the majority of the forest is 'secondary' forest and may contain large areas of jungle rubber and fruit tree enriched agroforests,
- for research concerned with the global C budgets and the effects of land use change on C emissions, priority should be given to the peat and wetland soils; drainage of 5% of the histosols may release more CO_2 into the atmosphere than transformation of all remaining forest into *Imperata* grasslands,
- no indication is obtained that tree-based production systems in plantation differ in C_{org} content from land used for annual crops.

2.2.3.3 Options for managing soil C and priorities for research

As emphasized by Lugo and Brown (1993), the prevailing concepts of change in soil C content due to changes in land use are too simple and possibly too pessimistic (if we agree that the highest possible soil C storage is the most desirable). There is a range of potential protection factors for soil C and land management options to increase their effectiveness are poorly explored.

From the data given here for Sumatra is seems that the protection of wetland soils and sites needs more attention if soil C storage is to be increased in the humid tropics. Changes in upland soil types are smaller than normally expected and will generally be less than 20 Mg C ha^{-1}. Within agricultural land use, soil tillage and liming operations should be considered critically as they affect two common C_{org} protection mechanisms. Although potentially reforestation on degraded grasslands leads to an increase in terrestrial C storage, the current techniques for large-scale reforestation of *Imperata* grasslands (based on intensive soil tillage to remove the grass, lime and fertilizer applications; Temmes, 1992) may have a negative effect on soil C storage, partly offsetting the gains aboveground.

Priorities for research on C sequestration in the humid forest zone should certainly include emphasis on sedimentation processes in colluvial and alluvial sites, ranging from a single hedgerow of trees to a river delta and on management effects on peat and other wetland soils.
As research priorities, we may continue to focus on a number of incompletely known inputs (esp. fine root turnover) and on developing methods which measure the most active fractions of soil organic matter, as well as those fractions still protected from microbial attack by one of the many protection mechanisms.

Finally, we may revisit the links between soil productivity and global C balance suggested by Sanchez *et al.* (1991), by quantifying the effects of replacing slash-and-burn farming by more intensive crop production systems. To do so, we will use the following parameters:
C_F = C stock of natural forest, averaged over its cycle length [Mg ha^{-1}].
C_S = C stock of shifting cultivation system, averaged over its cycle length [Mg ha^{-1}].
C_c = C stock of [permanently cropped field, averaged over its cycle length [Mg ha^{-1}].
a_c = part of total area needed for permanent crop production.
a_s = part of total area needed for shifting cultivation.
P_c = crop production rate of permanently cropped field [Mg ha^{-1} year^{-1}].
P_s = crop production rate of shifting cultivation system [Mg ha^{-1} year^{-1}].
P_{sc} = crop production rate of cropped part of shifting cultivation cycle [Mg ha^{-1} year^{-1}].
f_s = fallow: crop ratio of shifting cultivation system.
P_s and P_{sc} are related by $P_s = P_{sc}/f_s$.
If a constant crop productivity is required from either permanent cropping or shifting cultivation, we obtain:

$$a_c = \frac{a_s P_{sc}}{f_s P_c} \quad (2)$$

If the area not used for shifting cultivation or permanent cropping is covered by natural forest, we obtain for the total C stock associated with shifting cultivation, C_{sa}:

$$C_{sa} = C_f (1 - a_s) + a_s C_s = C_f - a_s (C_f - C_s) \quad (3)$$

and for the total C stock associated with permanent cropping, C_{sc}:

$$C_{sc} = C_f (1 - a_c) + a_c C_c = C_f - a_c (C_f - C_c) \quad (4)$$

Substituting (6) into (8):

$$C_{sc} = C_f - \frac{a_s P_{sc}}{f_s P_c} (C_f - C_c) \quad (5)$$

The C benefit of changing to permanent cropping and protecting the natural forest can now be calculated from:

$$C_{sc} - C_{sa} = a_s [C_f (1 - \frac{P}{\quad} \qquad P.$$

This difference is positive if

$$\frac{C_f - C_s}{C_f - C_c} > \frac{P_{sc}}{f_s P_c} \quad (7)$$

Table 2.2.4 Carbon mitigation options in agriculture, as summarized for the 1995 report of the Intergovernment Panel on Climate Change (IPCC) *(in preparation)*

A. Increased C stocks in agricultural soils

- A1. Increased use of local organic sources (crop residues, cover crops etc.).
- A2. Increased use of organic wastes from outside (town and agro-industrial wastes).
- A3. Slower turnover of soil organic matter (reduced tillage, reduced liming, etc.).

Tentative upper limit:
20 Mg C ha^{-1} (0.5 % C_{org} in upper 15 cm at b.d. 1.3 g cm^{-3}), distributed over a 50 year period: -> 2% of annual current fossil fuel C release. No further effects after 50 years.

B. C-stocks preserved or built up outside agriculture, made possible by increased productivity of agricultural soils

- B1. Development of forests and swamps on set-aside land in temperate zones with current overproduction.
- B2. Less conversion of tropical forests into agricultural use, based on intensification of agriculture and reclamation of 'waste' lands

Tentative upper limit:
Per doubling of productivity 150 Mg C ha^{-1} can be protected/sequestered outside agriculture (more in humid tropics, less in subhumid and semi-arid tropics and temperate zone, more where swamp development is possible). -> 10-15% of current fossil fuel C release.

C. Reduced C flows from fossil fuel use in agriculture

- C1. Lower energy use in storage and transport
- C2. Animal traction and other renewable energy sources
- C3. Reduced dependency on N fertilizer

D. Reduced C flows from fossil fuel use outside agriculture

- D1. Biofuel production

Tentative upper limit for C + D:
Upper limit 5-10% of current fossil fuel use, no time limit.

This condition will normally be met. For example, if C_f is around 400 Mg ha^{-1}, C_s is 200 Mg ha^{-1}, C_c = 50 Mg ha^{-1}, f_r = 10 and P_w = P_c, the inequality reads 0.57 > 0.1. For a more intensive fallow rotation with f_r = 3, C_s = 100 Mg ha^{-1} and P_w = 0.8 P_c, it reads 0.86 > 0.26.

If land not necessary for shifting cultivation is left under natural forest, an intensification of crop production thus indeed leads to an increased C storage in terrestrial ecosystems. However, permanent crop production depends on fertilizer inputs, to replace soil organic matter's role of nutrient supply; this fertilizer supply is based on an annual fossil fuel consumption, of X Mg ha^{-1} $year^{-1}$. Also, fossil fuel use will have to replace the fuelwood collected from the fallow vegetation previously, to the amount of Y Mg ha^{-1} $year^{-1}$. The initial advantage of the permanent cropping will thus turn into a disadvantage after $(C_{sc} - C_{pc})/(X + Y)$ years. Stimulating the transformation of shifting cultivation systems into more intensive permanent cropping systems, thus only gives a temporary benefit for the global C budget, which after some time will turn into a loss. The positive effect on biodiversity conservation of maintaining larger areas of natural forest along with more intensive crop production can be a lasting effect, however.

Table 2.2.4 summarizes the possibilities to reduce the impact of the rise in atmospheric CO_2 levels (which is largely due to fossil fuel use) by changes in agricultural practices. The problems can be mitigated by increasing C stocks in terrestrial ecosystems, both in (A) and outside (B) agricultural use, and by reducing flows of fossil fuel CO_2 to the atmosphere (C and D). The tentative orders of magnitude of the various options need further checking. The ASB project can contribute to this for the (humid) tropics. For the time being, the main reason to study soil C pools in more detail is their link with agricultural productivity and intensification of land use.