

# Monitoring Spatio-Temporal Changes of Soil Carbon in Java Using Legacy Soil Data

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**Abstract.** Legacy soil data is an important data source for digital soil mapping. While it is mostly used to provide the information on spatial distribution of soil, it also allows detecting temporal changes in soil properties. This work attempts to map the spatio-temporal changes in soil organic carbon (SOC) in the island of Java, Indonesia, using legacy soil data. We used 2002 soil profile data containing organic C analysis in the topsoil, which were collected by the Indonesian Center for Agricultural Land Resources Research & Development (ICALRD) from 1923-2007. Results show the obvious decline of SOC values from around 2 % in 1930-1940 to 0.7% in 1960-1970. However, there is an increase of SOC content after 1970, with a median level of 1.1% in the 2000. We aggregated the data into spatial administrative entities (kabupaten) and mapped the changes in every 10 years. Spatial analysis shows the trend of SOC over the island. Our analysis suggests that the human influence and agricultural practices on SOC in Java have been a stronger influence than the environmental factors. SOC for the top 10 cm has a nett accumulation rate of 20-30 g C m<sup>-2</sup> year<sup>-1</sup> (or 0.2 – 0.3 Mg C/ha/year) during the period 1990-2000. These findings raise optimism for increased soil carbon sequestration in Indonesia.

**Keywords:** soil carbon sequestration, tropical soils, Soil Information System, digital soil mapping.

## 1. Introduction

Many studies showed that soil can serve as carbon sink, but its ability differs among region and among soil depth within a region. In assessing the capability of soil to sequesters carbon, soil carbon stock should be first quantified. In fact, soil organic carbon (SOC) is known to decline with agricultural activities. Lal (2003) reported that the conversion of natural vegetation to cultivated lands can cause depletion of the SOC content by as much as 40% in temperate regions and 60% or more in the tropics. Davidson and Ackerman (1993) reported the mean loss of soil C inventory ranges from 24% to 43% of the carbon present in the uncultivated soil. In Indonesia, similar pattern is also found in Sumatera (Van Noordwijk *et al.* 1997; Lumbanraja *et al.* 1998), and Sulawesi (Dechert *et al.* 2005). Von Noordwijk *et al.* (1997) reported that on the major part of the upland soils the difference in (top) soil C content between natural forest and agricultural land is in the range 0.5-1.0% C, equivalent to a change in total C stock of 10-20 Mg ha<sup>-1</sup>.

It is also believed that SOC can accumulate when a soil is no longer cultivated and returns to supporting perennial vegetation or pasture (Guo & Gifford 2002; Post & Kwon 2000); or from conventional tillage to less intensive cultivation (West & Post 2002). Lugo & Brown (1993) estimated that tropical soils can accumulate between 168 and 553 Tg C/yr. It was proposed that soils in the tropics are more susceptible to losses of SOC as compared to temperate areas, as there is a greater proportion of highly weathered soils in the tropics and these soils are particularly sensitive to land management (Feller & Beare 1997).

To account such change, long-term research may provide such comprehensive data, however in Indonesia no soil monitoring network exists yet. There have been several local studies on the long-term dynamics of SOC: Van Noordwijk *et al.* (1997) in Sumatera, Van der Kemp *et al.* (2009) and Yonekura *et al.* (2010) in East Kalimantan.

Another way to asses soil properties change is by using legacy soil data. Legacy soil data is data collected from historical soil surveys with the purpose of mapping and done without any statistical criteria. The sampling procedure can be biased as usually it was done for a particular purpose. It is an important data source in digital soil mapping (Carré *et al.*, 2007), mostly used to provide information on the spatial distribution of soil, together with environmental or *scorpan* factors, they are utilised to develop spatial prediction functions for soil properties. However, legacy soil data can also be used to detect the temporal changes in soil properties. Lindert (2000) compiled a database of topsoil properties from Indonesia which were collected from 1930-1990. Using regression models, he showed the decline in soil organic matter and N content with time in Java and the increase in total phosphorus

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and potassium. This work was criticised by soil scientists, as the soil test results come from various places at various times, possible systematic bias due to unrepresentative repeated sampling, change in sampling depth, and/or change in analytical method over time (Dobermann, 2002a; 2002b; Yaalon, 2002). Nevertheless, recent work in France has shown that a nationwide soil test database can be used to detect decadal spatiotemporal changes in soil carbon (Saby *et al.*, 2008) and phosphorous (Lemercier *et al.*, 2008).

Our knowledge of the amount of C lost from soils clearly affects our characterization of the global carbon budget. This work provides the first estimates of spatio-temporal changes of soil organic carbon (SOC) over time in Java, Indonesia using legacy soil data collected from soil surveys conducted by the Indonesian Center for Agricultural Land Resources Research & Development (ICALRD). There has been little work that investigates the long-term changes in SOC over the whole island in the tropics.

## 2. Methods

### 2.1 Dataset

A dataset of soil properties from 1920-1990 was compiled by Lindert in the late 1990s (Lindert, 2000). The database contained best-detailed soil profiles gathered at the Indonesian Center for Agricultural Land Resources Research & Development (ICALRD), formerly known as Center for Soil and Agroclimatological Research (CSAR) in Bogor. We extended the Lindert database with new data obtained from recent surveys post 1990 conducted by the ICALRD. Here we are only looking at topsoil carbon content (0-10 cm depth) in the island of Java, which has a land area of approximately 139 000 km<sup>2</sup>.

The database covers time, space, and land use types unevenly. However all the samples were analysed by a single laboratory at the ICALRD, Bogor. There are 2002 soil profiles with SOC analysis. SOC content prior to 1950 was analysed using loss of ignition technique and reported as percent organic matter. The van Bemmelen factor of 1.7 was used to convert it to SOC. SOC after 1950 was mainly analysed using the Walkley and Black (1934) method. Figure 1 shows observation density for each kabupaten as recorded in database, where each dot represents one observation.

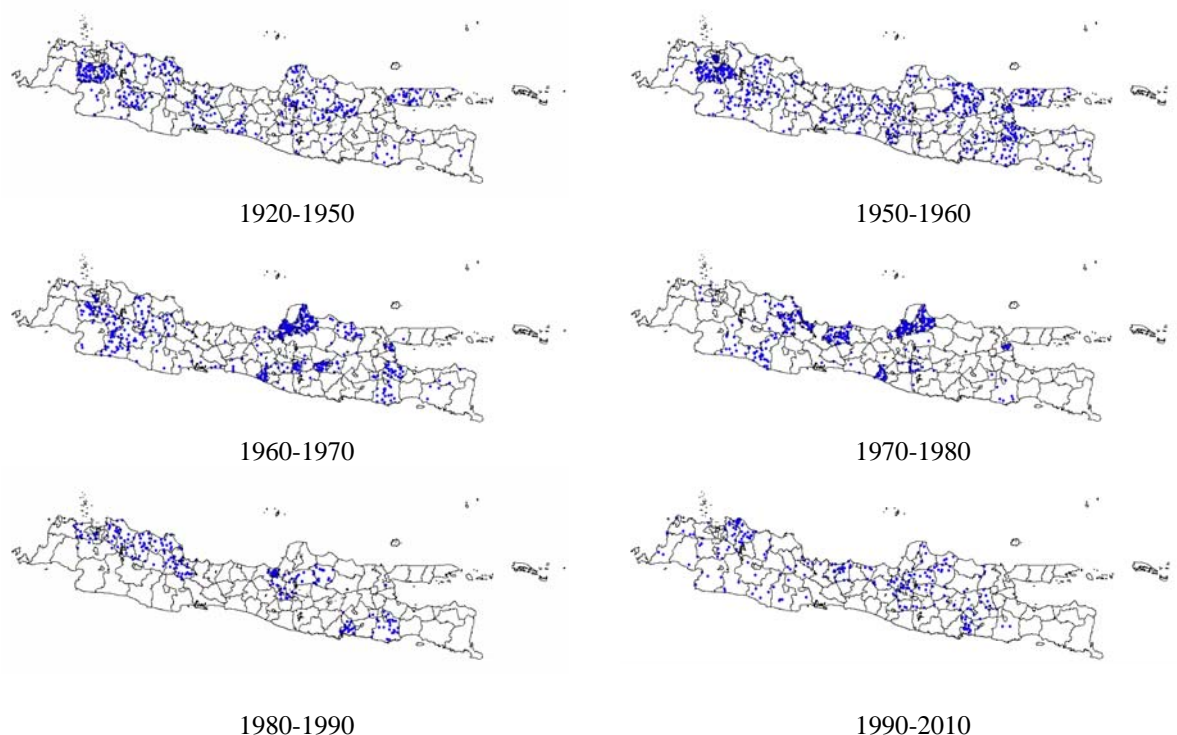


Fig. 1. The distribution of soil survey data for the kabupaten in Java.

The earliest date in the database is 1923, and the last date is in 2007. A large amount of soil survey occurred in 1940s during the Dutch colonials, and was cut short by the Japanese occupation. Soil survey peaked in the 1950-1960s after the Indonesian independence. The soil surveying program rotated among the islands. Java received a great coverage to about 1970, and has received less the attention since. However survey is still continuing for agricultural intensification with data continuing until 2007.

## 2.2 Spatial Representation

Most of the data pre 1980 do not have proper geographical coordinates; most are identified at the nearest village or town. Landuse is sometimes not recorded. We used the administrative area kabupaten or regency, which is an administrative division below the provincial government, as the geographical entity for the spatial representation of the data. The area of the kabupaten varies between 140 to 4000 km<sup>2</sup>, with a mean of 1500 km<sup>2</sup>. Data were aggregated for each kabupaten, for each decade from 1930. Summary statistics and spatial distribution analysis were performed on these data.

## 2.3 Soil Carbon Stock Calculation

We calculated carbon stock for the top 10 cm of the soil (in kg m<sup>-2</sup>). Since bulk density was rarely measured, it was predicted using pedotransfer functions. PTF for mineral bulk density for tropical countries was derived from the ISRIC database (Tempel *et al.*, 1996):

$$\rho_m = 0.935 + 0.049 \text{ Log}(\text{depth}) + 0.0055 \text{ Sand} - 0.0000653 (\text{Sand} - 38.96)^2 \quad (1)$$

where  $\rho_m$  is the mineral bulk density in g cm<sup>-3</sup>, depth is the mean depth of the sample (cm), and Sand is the percentage of sand content. Bulk density ( $\rho_b$ ) is then predicted from mineral bulk density adjusted for organic matter content, calculated using the model of Adams (1973):

$$\rho_b = \frac{100}{\frac{OM\%}{\rho_{OM}} + \frac{(100-OM\%)}{\rho_m}} \quad (2)$$

where  $\rho_b$  = adjusted bulk density in g cm<sup>-3</sup>, OM% = organic matter percentage, and  $\rho_{OM}$  = organic matter bulk density = 0.224 g cm<sup>-3</sup>.

Carbon stock in 10 cm depth or C density (kg m<sup>-2</sup>) was calculated as:

$$\text{C density (kg m}^{-2}\text{)} = (\text{C}\%/100) \times \rho_b \text{ (kg m}^{-3}\text{)} \times \text{soil depth (m)} \quad (3)$$

Carbon stock for each kabupaten (in kg) was calculated as:

$$\text{C stock (kg)} = \text{C density (kg m}^{-2}\text{)} \times \text{Area of the kabupaten (m}^2\text{)} \quad (4)$$

## 3. Results

### 3.1 Soil Organic Carbon Dynamics in Java

The SOC content for topsoils in Java with time is showed in Figure 2. Java is the most crowded island in Indonesia, where 58 % of Indonesian population live (BPS, 2010). Java has richest soil from volcanic activities (Inceptisols, Andisols) and large floodplains (Entisols). Meanwhile, in our dataset, the dominant soil is Inceptisols, covering 60% of the database. Its land is most intensively farmed, and thus the SOC trends reflect human activities over time. We can see a rapid decline of SOC from 1930s to 1960.

The initial SOC drop is mostly due to the high conversion of forests into plantations and food crops. In the early development during the Dutch colonialism, most land development is towards plantations such as tea, rubber, coffee, tobacco, etc. This is followed by rapid conversion to food crops in the 1950s, leading to a massive rice production in the 1960s. The green revolution in the late 1960s was fully implemented through government program, with Java producing about two-thirds of the country's rice. This resulted in a rapid decline of 1.5% of SOC. The conversion of natural forests to agriculture in the humid tropics leads to a reduction in ecosystem carbon storage due to the immediate removal of aboveground biomass and a gradual subsequent reduction in soil organic carbon (van Noorwidjk *et al.* 2007).

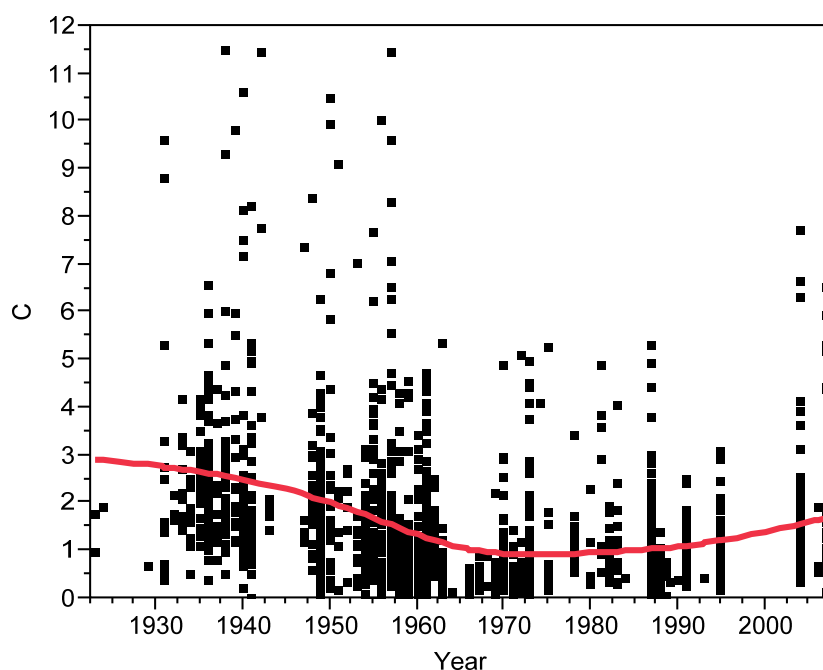


Fig.2. Soil organic C content (%) over time for top soils (0-10 cm) in Java

Following the decline, there is a slow increase of SOC after 1970s. This is the result of the government program and farmers' effort to remediate the soil fertility by adding fertilizers, returning crop residues, and applying green compost and manures, and pest control as well. In the 1990s also there is a large interest in organic farming. SOC content has risen to a level of 1.1% in the 2000s. Lindert (2000) observed a rapid decline of organic matter in the topsoil since 1940, with a large drop to 1970 and a lesser rise thereafter. Our analysis displays the obvious increase of SOC after 1970.

Table 1 shows SOC content and SOC stock grouped by decade. In 1930-1940 observation the median of SOC content is 2.11 % then decrease to 0.75 % in 1970-1980. After that the median of SOC content increase to 1.18 %. Such increase however is still lower than the initial one. In other word there is rapid SOC loss during initial period to 1970's and then SOC slowly stabilized since 1970s to recent.

As expected, the median of SOC stock shows similar pattern with SOC content. The SOC stock decrease  $1.34 \text{ kg m}^{-2}$  during 1930-1980 period and then increase  $0.51 \text{ kg m}^{-2}$  since 1980s to present. This mean that there is C sequestration process during 1980's to present. However, the recent stock ( $1.21 \text{ kg m}^{-2}$ ) is still lower than the initial one ( $2.04 \text{ kg m}^{-2}$ ).

Table 1. Soil C content and C stock (in 0-10 cm depth) of Java soils, grouped by decades

Obs.year	No.obs	C content (g.100g <sup>-1</sup> )			C stock (kg.m <sup>-2</sup> )
		Minimum	Median	Maximum	Median
1930 - 1940	282	0.35	2.11	11.64	2.04
1940 - 1950	183	0.13	1.79	11.58	1.84
1950 - 1960	437	0.04	1.15	11.58	1.14
1960 - 1970	434	0.07	0.76	5.47	0.73
1970 - 1980	223	0.09	0.75	5.40	0.70
1980 - 1990	209	0.06	0.79	5.44	0.80
1990 - 2000	77	0.31	1.08	3.20	1.09
2000 - 2010	157	0.24	1.18	7.82	1.21

### 3.2 Mapping Soil Carbon Dynamics

Since not all areas in Java were sampled evenly, we aggregated the data in time and space. First we divided the time into 6 periods: 1930-1950, 1950-1960, 1960-1970, 1970-1980, 1980-1990, and 1990-2010. Secondly, we selected the kabupaten which have at least 4 observations within the 6 periods. Forty six (out of 84) kabupaten were identified. For each kabupaten, the median value for SOC content (percent) and SOC stock (in Tg, where 1 Tg = 1 Mton) for each time period were calculated. Missing values between the periods were interpolated using spline functions. Thus, we obtain a representation of C content and stock over space and time.

Figure 3 shows the dynamics of soil carbon from 1930 to 2010 and Figure 4 shows the C stock difference for each of the time period. Areas in the Southwest of Java appear to have the highest SOC content. These areas correspond to upland areas with high rainfall. The landuse is mainly forests and plantations. Meanwhile areas in the east of Java with dryer climate have the lowest C content, corresponding to areas of crops and rice production.

The general spatial trend shows that from 1930 to 1960, there is a huge drop of soil C content all over the island. After 1970, there is slow increase of carbon. Areas in West & Central Java show higher soil C content with an accumulation rate during 1990 to 2000s of 25-45 g C/m<sup>2</sup>/year. Meanwhile areas in east of Java has lower soil C content and very low accumulation rate of 1.5 g C/m<sup>2</sup>/year.

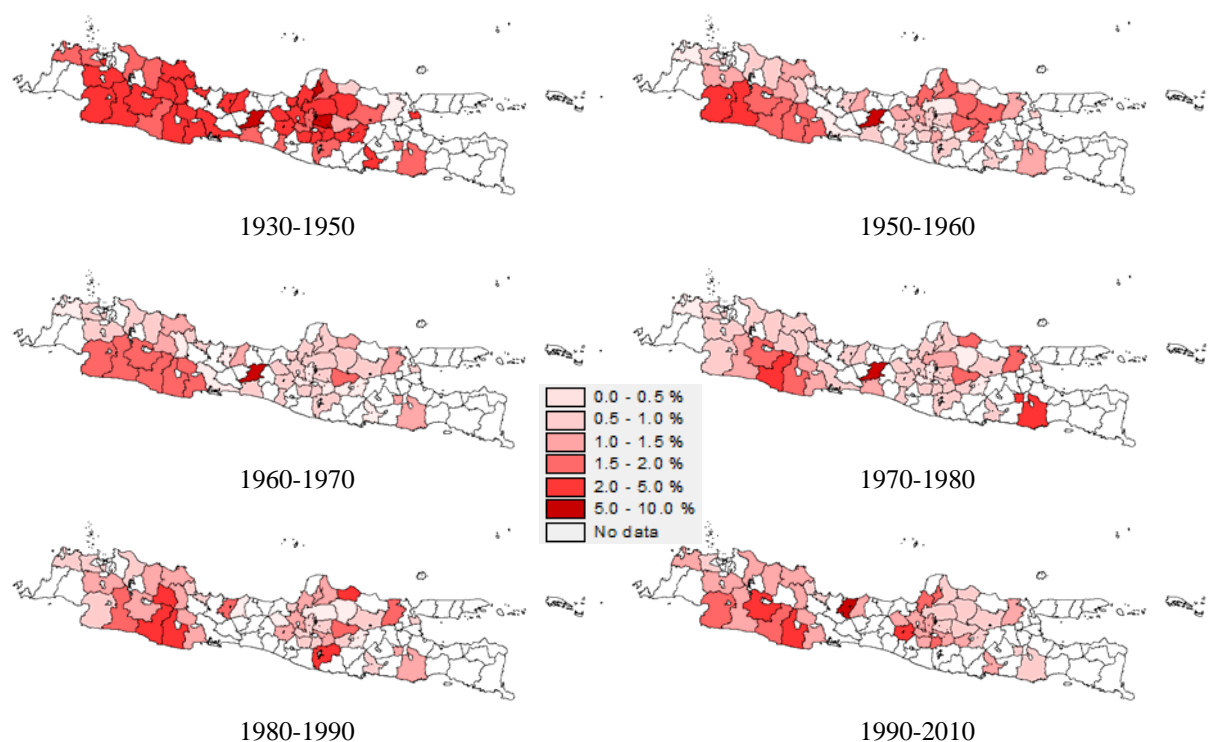


Fig. 3. The evolution of organic C content for the top 10 cm soil in Java



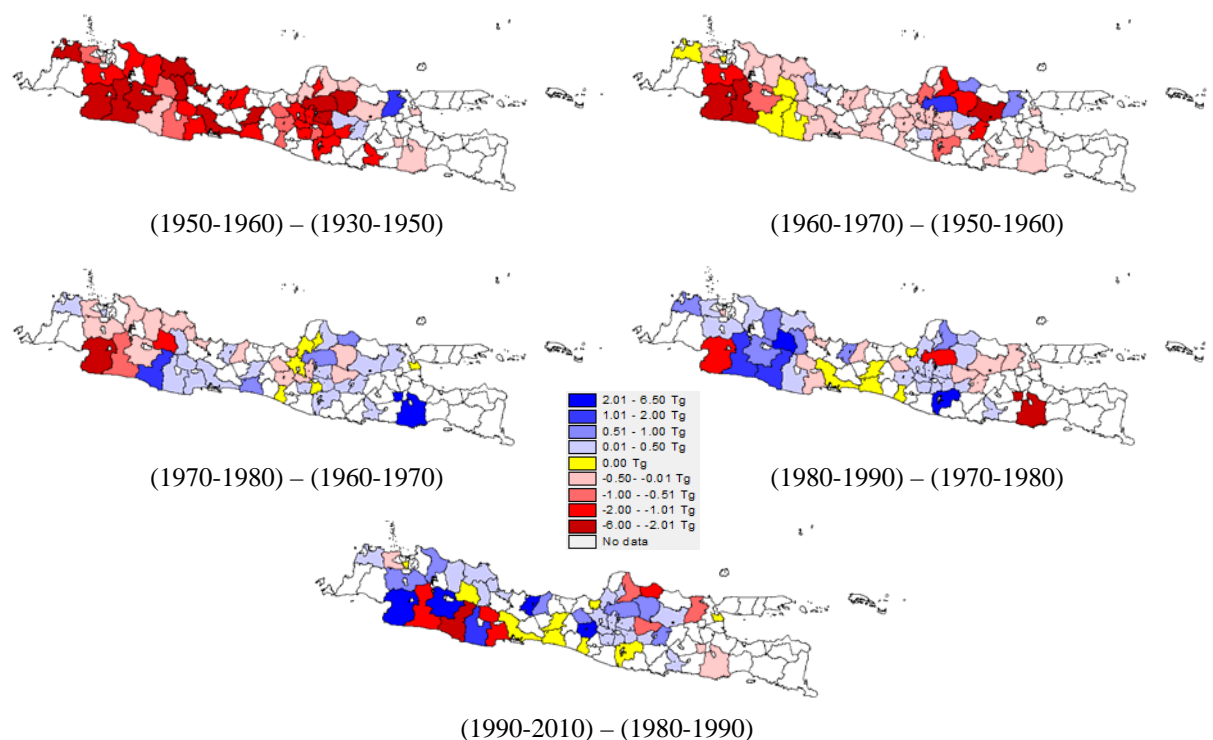


Fig.4. The changes in C stock over successive period for the top 10 cm soil in Java

## 4. Discussion

### 4.1. Legacy soil data for monitoring soil properties

Surface soils, forming the largest pool of terrestrial organic carbon, may be able to sequester atmospheric carbon and thus mitigate climate change. However, this remains controversial, largely due to insufficient information on SOC stocks worldwide. One reason for this is the generally limited number of available data points, especially when large areas are considered (Phachomphon *et al.*, 2010). In this study we make use legacy data in form of point soil observation. This data is currently stored in digital databases and soil survey reports as well.

There is some digital soil database in Indonesia, in addition to hardcopy documents. Lindert's database (Lindert, 2000) and Soil Hydrolic Database (Sulaeman & Hikmatullah, 2006) which both are digital point soil observation database. Both store soil properties such as soil organic carbon, particle size distribution, sample location, etc. There is also PKDSS's database storing soil test data of surface soil primarily from soil fertility research on agricultural soils. SHDE4 is used mainly for storing profil description including datasite and horizon and SSA for storing soil sample analysis for each soil depth of soil profile. While SHDE4 and SSA is DOS based, SHFox used to store site and horizon is Windows based. There is also dataset stored in other research institutes over country in form of spreadsheet or reports.

As basic part of soil information system, these database store huge dataset that can be used among others: (i) to get more insight about Indonesian Soils, (ii) to monitor change of soil properties, (iii) to map magnitude and uncertainty of soil properties as proposed in digital soil mapping approach, and (iv) to develop spatial prediction models and pedotransfer models (Lagacherie & McBratney, 2007) so that using this model coupled with application DSM, data from unsampled area can be estimated and soil sampling design for further study can be formulated. Recently Pachomphon *et al.* (2010) demonstrated DSM technique to estimate carbon stock in Laos.

Another form of legacy data is historical soil maps. It also may be used to monitor carbon change temporarily and spatially. Useful knowledge (e.g. soil organic carbon distribution over

landscape) can be retrieved from soil maps and their legend (Bui, 2004). But, such reanalysis of existing soil maps to study dynamic of soil carbon is scarce. Digital soil mapping (DSM) provides tools to manage and reanalysis this unused data. Analyzed with proper methods, this existing map has great significance for environmental and agricultural assesment and monitoring locally, regionally, and globally. More collaborative approach among data owner nationally and regionally is requires so that the benefit of this legacy data can be extended.

Legacy soil data, however, poses various problems. Firstly, it has uneven geographic coverage at different periods. Soil observation and soil mapping is usually conducted for particular purpose for particular area of concern. It can be found, there is no legacy data for a given region for particular period since this region is still undeveloped. In our study, to remediate the blank soil carbon data for a given periode, we use statistical analysis for estimating this data. Our study only concern on region having legacy soil data, so there is blank data for several kabupaten. However, DSM techniques provide tools to estimate soil carbon content and its uncertainty. This approach may be used for further studies.

Other problem of legacy data is the consistency and accuracy of laboratory methods used is unknown. There may be some uncertainties in these analyses, however we are not able to verify them. Nevertheless, our empirical analysis are able to show the dynamics of soil organic C over the island. This is because the soil in Java has been intensively cultivated, and most soil surveys were conducted for agricultural intensification purposes.

#### 4.2. Monitoring soil organic carbon

Monitoring long-term trend in soil C over large areas is rare as long-term sampling schemes are uncommon. Furthermore, the slow rates of change and large spatial variation in soil C require high sampling density and sufficient time period to observe changes. Saby *et al.* (2008) demonstrated that historical soil test results, which were not originally intended for monitoring, can provide an alternative method for detecting changes in soil organic C over a large area.

Since there is no soil monitoring scheme in Indonesia, the legacy soil survey data is the best information to observe the dynamics of soil C. Although the survey data only measure representative profile or land unit, they prove to be valuable source of temporal information. Unlike the French study, this study doesn't have the luxury of the data; it only has a smaller number of data covering a much larger area.

#### 4.3. Land Management Implementation

There are for main process being responsible for the loss of SOC i.e. soil redistribution (Gregorich *et al* 1998, Pennock *et al* 1994), changes in mineralization because of altered soil moisture condition (Janzen *et al* 1997), leaching of soluble organic C (Gregorich *et al* 1998) and decreases in C input (Janzen *et al* 1998). Slobodian *et al* (2002) concluded that landscape position govern SOC loss. Root growth and its relationship to SOC dynamic is sensitive to landscape position to its influence on soil moisture and fertility

In this study we show the change of soil carbon content over time (Figure 2). This change reflects the change in human intervention to soil process. Conversion of natural forests to agriculture leads to a reduction in ecosystem carbon storage due to the immediate removal of aboveground biomass and a gradual subsequent reduction in soil organic carbon (van Noorwidjk *et al.* 2007). With this forest conversion C input to soil decreases. The reduction in soil organic carbon is due to soil erosion which bring upper soil to lower landscape so that s oil volume in the remaining site decrease. Hence, carbon stock decrease. Lower canopy coverage lead to soil agregate destruction by rainfall. This proces make soil carbon within aggregate expose to microbial attack so that soil content decrease.

Carbon sequestration by agricultural soils has been widely promoted as a means of mitigating greenhouse gas emissions (Bedard-Haughn *et al.* 2006). The potential for different landscape elements to sequester carbon is partly dependent on the changes in SOC stores that have occurred since cultivation began. Losses reflect both erosional loss and decomposition of newly exposed SOC. The potential for eroded landscapes to serve as a CO<sub>2</sub> source due to aggregate breakdown, the resulting

SOC oxidation, and reduced fertility (McCarty & Ritchie, 2002) can be partly offset by their potential to serve as an active sink.

To increase and maintain soil carbon stock, best practice of land management may be implemented. Agroforestry particularly alley cropping and SALT (sloping agricultural land technology) systems appear to be promising alternative. But in reality cultivators do not necessarily respond positively to this alternative in spite of strong recommendation by researcher and extension worker (Kyuma 2003). It seems necessarily just not to prove technically sound but to have more insight into the psychology and behavioral patterns of cultivator.

Another potential techniques to sequester carbon are residue management and soil fertility management. Residue management store plant residues landing the soil. Burning residues in some parts of cultivation must be stopped. Application of compost, manure and residues management have been introduced in Indonesia since 1970s.

In soil fertility management, fertilizer application not only can replace nutrient lost due to plant harvest, but also can promote better plant growth and biomass production. This biomass may absorb CO<sub>2</sub> atmosphere and turn it as carbohydrate and biomass during photosynthesis. Higher nutrient level within soil increase lateral root production, while low nutrient level increase root length. Fertile soil support shallower denser root systems and their lesser fertile counterpart (Slobodian et al. 2002). In Java, fertilizer application has commonly been implemented since BIMAS (Resosudarmo & Yamazaki, 2010).

#### 4. Conclusions

Our study has demonstrated the use of legacy soil data particular point soil observation in monitoring spatio-temporal dynamic of SOC in Java. Making, improving and populating soil information system that manage legacy soil data should be promoted so that assessment soil carbon budget can be improved and extended. There need to be a coordinated effort to compile all existing soil databases into a national database.

Soil organic content in Java decrease upto 1970 and then increase after that time. There is also found that carbon stock change differ among region kabupaten in time and in magnitude reflecting different time adoption on best land management practices in addition to land use.

Our analysis suggests that the human influence and agricultural practices on SOC in Java have been a stronger influence than the environmental factors. SOC for the top 10 cm has a net accumulation rate of 20-30 g C m<sup>-2</sup> year<sup>-1</sup> (0.2 – 0.3 ton C/ha.year) during the period 1990-2000. These findings raise optimism for increased soil carbon sequestration in Indonesia.

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