Controls on Soil Development and Carbon Storage on the High-Standing Island of Taiwan

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation
with research distinction in Geological Sciences in the undergraduate colleges
of The Ohio State University

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December 2010

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Abstract

Studies on weathering rates of high standing islands (HSIs) have shown high observed rates of chemical weathering. However, attempts to correlate these rates to sources have often suffered due to a lack of sufficient soil geochemical data. Furthermore, few studies have attempted to determine a relationship between soil organic carbon content, storage, and seq uestration with uplift and erosion rates. Taiwan sits on top of a highly active convergent plate boundary between the Eurasian and Philippine Sea Plate, which results in intense uplift, creating the orogenic mountains that make up the island. The plate margin has uplift rates >10 mm/yr and contains erosional features dominated by mass-wasting. The island also contains three of the nine rivers in the world which have average sediment concentrations >10 g/l (Milliman and Syvitski, 1992). This study determined organic carbon, inorganic carbon, and a relative amount of weathering in soils between three locations on Taiwan with different lithology and seismicity and with various rates of uplift, runoff, and erosion. Soils exhibited relatively higher concentrations of organic carbon and more developed soil profiles in areas where these erosional factors play a limited role.

Acknowledgements

I am very thankful to my advisor, Anne Carey, for endless support and guidance throughout my undergraduate research career. I am also very grateful for the help and influence that Steve Goldsmith and Sue Welch were able to provide me in being able to present and understand the project. I would also like to acknowledge Steve Goldsmith for the collection of the samples and training in the methodology associated with this project. I am grateful for the partial funding provided by the Ohio State University School of Earth Sciences, the Byrd Polar Research Center, the Undergraduate Student Government, the Denman Undergraduate Research Forum, Friends of Orton Hall, the McKenzie Scholarship, and the Geological Society of America. I am also thankful to Wendy Panero who networked me with Anne and Steve so I could start my undergraduate research career. I would like to acknowledge my committee members; Dr. Anne Carey, Dr. W. Berry Lyons, and Dr. David Porinchu for their commitments to improving my senior thesis presentation and writing. Lastly, I must thank my family and friends for their continued support and motivation.

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Introduction

Of the three main geologic resetting events; glaciers, volcanism, and uplift, high-standing islands (HSI) are heavily influenced by the latter. Taiwan is considered an HSI since it has rivers whose headwaters are greater than 1,000 meters in elevation. Some of the highest rates of chemical weathering and CO_2 consumption have been shown in previous studies of HSIs like Taiwan (Lyons et al., 2005; Carey et al., 2005). Soil samples were collected in 2005 from three different locations on the island to identify the controls on the soil's development. Uplift rate, erosion rate, lithology, seismicity, and episodic precipitation events were noted for each location as factors that could influence soil weathering and development. Particle size, organic matter content, and major element chemistry via the sieve, loss on ignition, and x-ray fluorescence methodology accompanied with previous studies on the bedrock and the various factors previously mentioned can be used to identify what controls the development and carbon consumption of soils on the island's surface. I hypothesize that a combination of erosion factors will produce the most weathering of the soils versus one or none and that the locations experiencing minimal influence of these factors will exhibit more deeply developed soil profiles and carbon contents.

The overall goal of this project is to identify the main erosional factors affecting carbon storage and soil development. This entails identifying differences in the three locations' soil profiles with the previously mentioned analytical methods that provide evidence for weathering and carbon storage. The data found from this study can be compared to other HSIs around the globe with similar and different erosional factors to better understand carbon storage and soil development.

Background, Geologic Setting, and Sampling Locations

Taiwan was formed by an oblique collision of the Eurasian plate beneath the Philippine Sea plate creating multiple subduction zones and the intense uplifting and compression of its central range thus forming a mountain range in the Pacific Ocean (See Figure 1). This orogenic uplift is made possible by multiple thrust faults, including the Chelungpu fault where the 1999 Chi Chi earthquake occurred. The earthquake in Taiwan's central range relieved accretionary pressures and allowed shortening in the horizontal NW to SE direction and extension in the vertical direction.

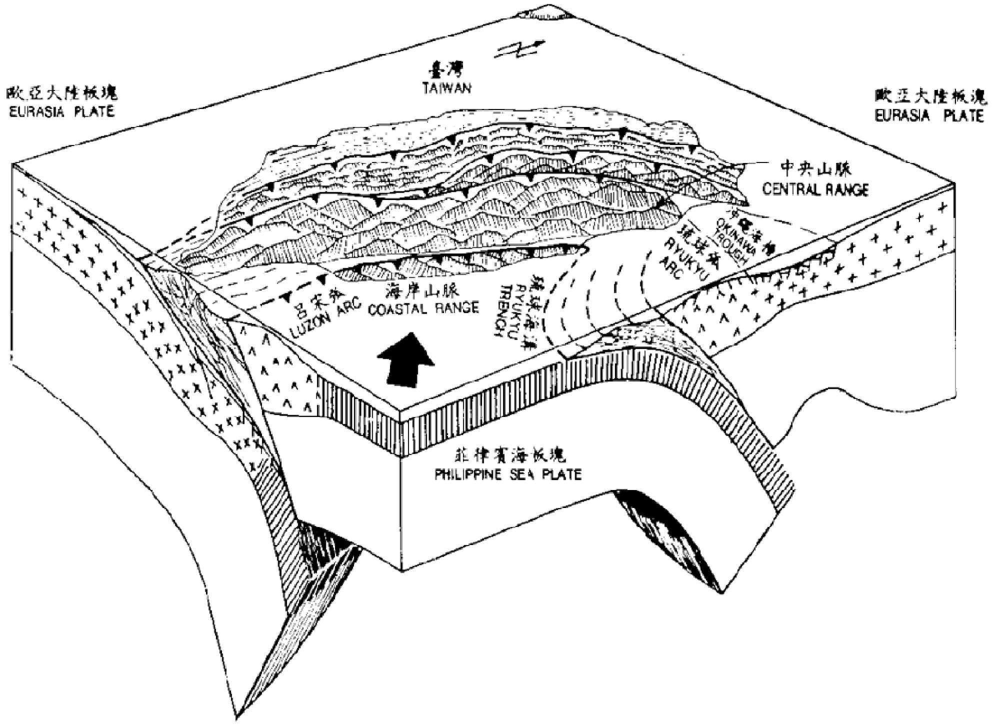

Figure 1. Plate tectonics of the Taiwan Region (Ho, C.S., 1975)

Characteristics of Taiwan

Uplift rates of greater than 10 mm yr^{-1} have been recorded along the island and the resulting metamorphic grade and shortening factor creates drastically changing lithologies as seen in Table 1. (Ho, 1988; Shin and Teng, 2001; Dadson et al., 2003). These lithologies range from a completely sedimentary and highly friable mudstone of the low lying Choshui Watershed to a very rigid quartzite in the elevated central range in the Fushan Experimental Forest. As seen in Figure 2, the metamorphic grade and shortening vector are the highest in the central range where the uplift of the central mountain range is present. The earthquakes produced by the seismicity associated with the islands uplift induce landsliding and rock shattering that allows fresh bedrock surfaces to be exposed. The largest earthquakes of the three sites are located between the western and central ranges on Taiwan near the Choshui Watershed.

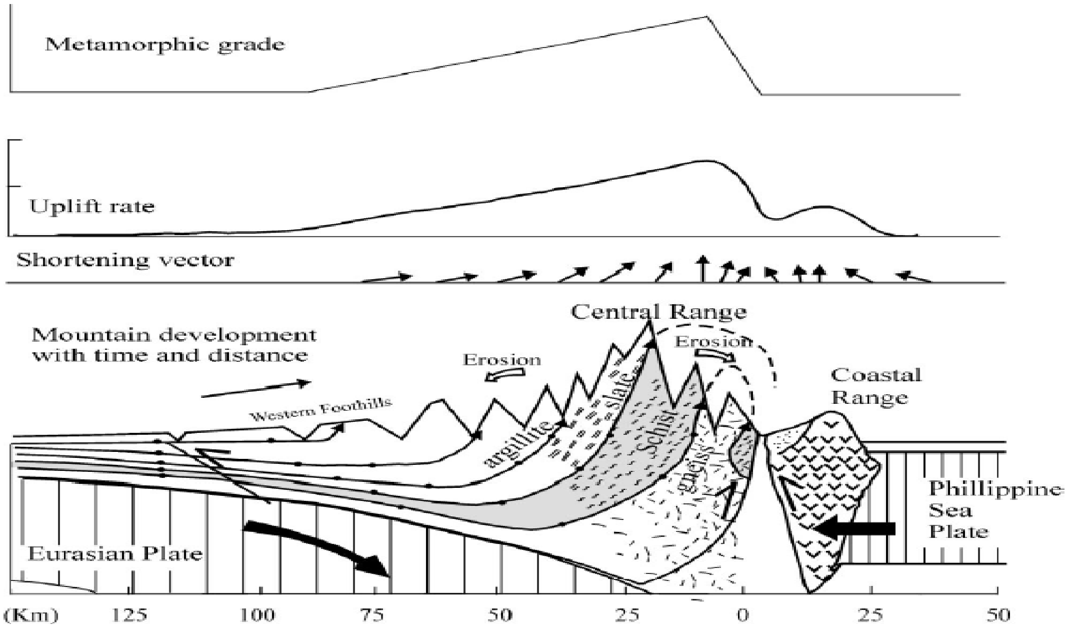

Figure 2. Taiwan’s Geologic Formation in cross-section view (from Liu et al., 2000)

Not only are multiple lithologies and seismicities present, but also a range of runoff rates for different locations seen on the island. The island receives an average of four tropical typhoons annually that distribute significant portions of precipitation across the island. The average annual precipitations for the three locations ranged from 4450 mm in the Fushan Experimental Forest to 2017 mm in the Choshui Watershed (Lin et al., 2000 and Tsao, 1987). Most of this precipitation was due to typhoons which also create hyperpycnal streamflows and significant erosion of the vegetation and slopeland. These extreme storm events allow for channeling of the sediments to more remote ocean basin environments (Goldsmith et al., 2008: Lin et al., 2008). The island has three rivers which have annual sediment concentrations greater than 10 g/l (Milliman and Syvitski, 1992).

Rapid uplift of the region leads to high rates of physical erosion by mass-wasting, which allows more surface area of fresh bedrock to be exposed for subsequent chemical weathering. This chemical weathering is dominated by a silicate weathering cycle. Silicate weathering is able to consume 2 mole of CO_2 on land and only release 1 mole of CO_2 in the ocean for a net draw down of 1 mole of CO_2 for the overall cycle. This overall process acts as the only geological long-term sink of CO_2. The following equations from Berner (2004) describe this cycle:

On land:

(Eq. 1.1) $\mathbf{2CO_2 + 3H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3 + H_4SiO_4}$

Carbon Dioxide + Water + Calcium Silicate Mineral → Calcium Ion + Bicarbonate Ion + Silicic Acid

As atmospheric CO_2 reacts with water and a calcium silicate mineral, a Calcium ion and Bicarbonate ion are released along with silicic acid.

In the Ocean:

(Eq. 1.2) $\mathbf{Ca^{2+} + 2HCO_3 \text{-->} CaCO_3 + CO_2 + H_2O}$

Calcium Ion + Bicarbonate Ion → Calcium Carbonate + Carbon Dioxide + Water

The calcium and bicarbonate ions are transported down to the oceans where they react to release 1 mole of CO_2 and precipitate 1 mole of CO_2 in the form of calcium carbonate.

Table 1. Sample Location Summary

Sample Location	Uplift Rates[1] (mm/yr)	Lithology[2]	Mean Precipitation (mm/yr)	Dominant Vegetation Species	Seismicity[†]	Erosion Rates[†] (mm/yr)
1. Fushan Experimental Forest	5-10	Sandstone, shale, argillite, phyllite, slate, and quartzite	4450[3]	*Castanopsis carlesii, Litsea acuminate, Diospyros morrisiana, Elaeocarpus japonicas, Persa thunbergii, Persea zuihonesis, Meliosma squimulata*, and *Pyrenaria shinkoensis*[3]	3 earthquakes of $M_w > 6.0$ 1900 - 1998	2-8
2. Yuan-Yang Lake	5-10	Shale, argillite, and phyllite	4000[4]	*Chamaecyparis obtuse* var. *formosana, Chamaecyparis formosensis,* and *Rhododendron formosanum*[4]	3 earthquakes of $M_w > 6.0$ 1900 - 1998	3-6
3. Choshui Watershed	5-10	Sandstone, mudstone, shale, argillite, and phyllite	2017[‡]	Paddy rice fields[‡]	11 earthquakes of $M_w > 6.0$ 1900 - 1998	3-10

[1]Shin and Teng, 2001, [2]Ho, 1988 [3]Lin et al., 2000, [4]Klemm et al., 2006, [‡]Tsao, 1987, [†]Dadson et al., 2003

Location 1. Fushan Experimental Forest

The Fushan Experimental Forest is a relatively undisturbed typical moist, subtropical, mixed evergreen forest located in the north-central range of Taiwan (Lin et al., 2000). It experiences a moderate amount of uplift and a slightly metamorphosed sedimentary lithology that experiences a large amount of runoff due to precipitation, but little seismicity in comparison to other sites on the island (Table 1).

Location 2. Yuan-Yang Lake

Yuan-Yang Lake is a nature preserve characterized by a small monomictic lake Cypress forests in a temperate heavy moist climate located in the north-central range of Taiwan (Jones et al., 2009). The cypress forests had been extensively logged in the past, but are now protected by the national nature preservation regulations (Klemm et al., 2006). The site experiences intense uplift coupled with a metamorphosed sedimentary lithology that undergoes significant runoff and minor seismicity when compared to other sites on the island (Table 1).

Location 3. Choshui Watershed

The Choshui Watershed is a low gradient river system located on the Western Foothills of western Taiwan that includes the longest river in the country, the Zhuoshui River, and the magnitude 7.7, 1999 Chi-chi earthquake (epicenter = 23°46’19.12”N, 120°58’55.18”E at 33 km depth). The Choshui River alluvial fan is the most important agriculture area in western-central Taiwan (Liu et al., 2004). This site experiences very little uplift and weak friable sedimentary and low-grade metamorphic rock lithologies with an intense amount of runoff and significant amounts of seismicity (Table 1).

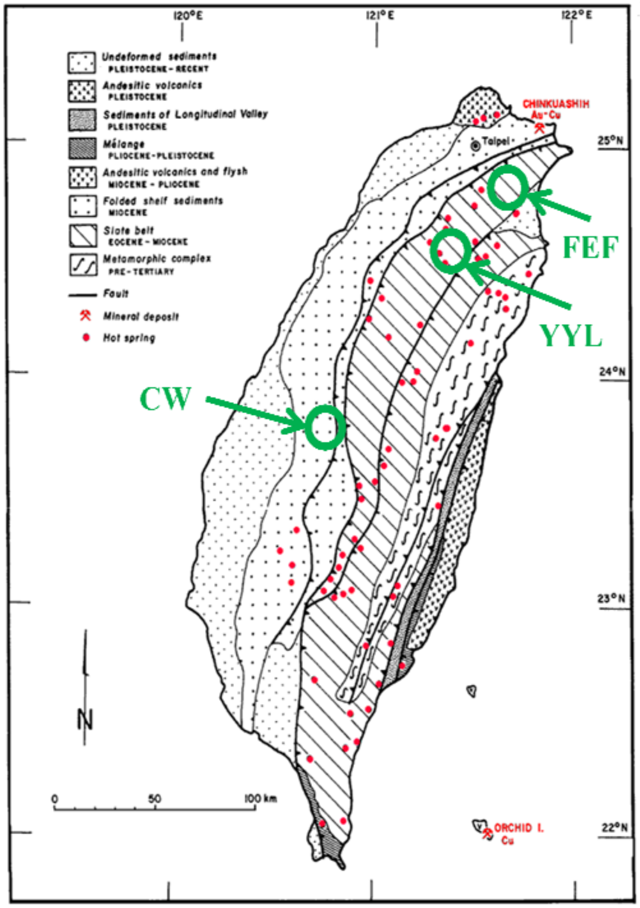

Figure 3. Sample locations (CW = Choshui Watershed, YYL = Yuan-Yang Lake, FEF = Fushan Experimental Forest), Lithology and Fault lines of Taiwan. (Figure modified from Jones et al., 1823)

Methods

Sampling Methods

Sixteen soil profiles were obtained from three geographically different regions on the island of Taiwan. Samples were collected from locations that experience varying degrees of previously discussed factors (lithology, runoff, seismicity, and uplift induced erosion). These areas include the Choshui Watershed in the western range and the Taiwan Ecological Research Network (TERN) sites of the Fushan Experimental Forest and the Yuan-Yang Lake in the central range (See Table 2). These soil profiles were collected as cores by digging a pit and sampling cores at specific intervals from within the pit. Each soil profile core collected consisted of depth intervals of 0-5 cm, 5-10 cm, 10-15 cm, and 15-30 cm that were separated into four different containers corresponding to each specific depth interval before being returned to Ohio State for analysis. These samples were stored in plastic containers and were sealed by black electrical tape and placed in Ziploc bags within a cooler to prevent the soil contents from mixing with each other and the atmosphere. These cores were then shipped to Ohio State and stored in the laboratory room until analysis.

Table 2. Sample Interval and Location

Sample Name	Intervals (cm)	Locality	Latitude/ Longitude	Elevation (m) & Slope (m/m)
SC-1 (TERN site)	0-5, 5-10, 10-15, 15-30	Fushan Experimental Forest	N 24°45.149/ E 121°35.102	616 and 0.140
SC-2 (TERN site)	0-5, 5-10, 10-15, 15-30	Fushan Experimental Forest	N 24°45.952/ E 121°35.123	712 and 0.327
SC-3 (TERN site)	0-5, 5-10, 10-15, 15-30	Fushan Experimental Forest	N 24°45.972/ E 121°35.140	727 and 0.423
SC-4 (TERN site)	0-5, 5-10, 10-15, 15-30	Fushan Experimental Forest	N 24°46.048/ E 121°35.101	785 and 0.330
SC-5 (TERN site)	0-5, 5-10, 10-15, 15-30	Fushan Experimental Forest	N 24°46.115/ E 121°35.170	832 and 0.301
SC-6 (TERN site)	0-5, 5-10, 10-15, 15-30	Fushan Experimental Forest	N 24°45.897/ E 121°35.218	689 and 0.101
SC-7 (TERN site)	0-5, 5-10, 10-15, 15-30	Yuan-Yang Lake	N 24°35.358/ E 121°24.625	1718 and 0.604
SC-8 (TERN site)	0-5, 5-10, 10-15, 15-30	Yuan-Yang Lake	N 24°35.358/ E 121°24.625	1718 and 0.604
SC-9 (TERN site)	0-5, 5-10, 10-15, 15-30	Yuan-Yang Lake	N 24°34.630/ E 121°24.660	1712 and 0.161
SC-10 (TERN site)	0-5, 5-10, 10-15, 15-30	Yuan-Yang Lake	N 24°35.444/ E 121°24.768	1716 and 0.403
Sample Site C (Soil #1)	0-5, 5-10, 10-15, 15-30	Choshui Watershed	N 23°43.145/ E 120°40.136	216 and 0.276
Sample Site C (Soil #2)	0-5, 5-10, 10-15, 15-30	Choshui Watershed	N 23°43.145/ E 120°40.136	216 and 0.276
Sample Site R (Soil #1)	0-5, 5-10, 10-15, 15-30	Choshui Watershed	N 23°46.487/ E 120°52.177	529 and 0.340
Sample Site R (Soil #2)	0-5, 5-10, 10-15, 15-30	Choshui Watershed	N 23°46.487/ E 120°52.177	529 and 0.340
Sample Site S (Soil #1)	0-5, 5-10, 10-15, 15-30	Choshui Watershed	N 23°41.454/ E 120°51.115	Flat floodplain
Sample Site S (Soil #2)	0-5, 5-10, 10-15, 15-30	Choshui Watershed	N 23°41.454/ E 120°51.115	Flat floodplain

Laboratory Procedures

The plastic containers were removed from their Ziploc bags. The containers were then opened and the soils were put into clean, numbered and tared glass beakers. The beakers were placed in an oven at 110°C for 96 hours to dry. The emptied plastic containers were dipped in a 10% bleach solution, washed with Citranox solution and rinsed with distilled water to remove any invasive species.

Particle Size Separation

The dried soil samples were sieved by placing the sample in the top compartment of the U.S. Standard Testing Sieve by The W.S. Tyler Company. Samples were shaken with a Sieve Testing Equipment Laboratory Apparatus (Humboldt Mfg. Co.) for 15 minutes. The sample was separated into the three different particle size compartments of <63µm (fines), 63µm to 2mm (sand), and >2mm (gravel) and were then placed into separate clean plastic containers based on depth and particle size within each soil profile.

Bulk Density

One bulk density for each core was determined on a separate sample of known volume as the total dry weight divided by the volume of the sample. The corer volume was 300.41 cm^3.

Organic Matter

Organic matter analysis by loss on ignition (LOI) was conducted to determine the fraction of organic carbon, inorganic carbon, and bound water in the soil profiles. Three aliquots of 2 grams of soil sample were weighed and each put into porcelain Coorstek crucibles for each profile depth with two other soil profiles and combusted in a Fisher Scientific Isotemp muffle furnace.

To find the organic carbon content, the crucibles were placed into the middle of a pre-heated furnace at 550°C for 4 hours to burn off any organic matter (Ball, 1964; Hieri et al., 2001). Using Hunt's method (1981), 33% of the loss on ignition was considered organic carbon weight loss of the total weight loss. The following equation was used:

(Eq. 2.1) $LOI_{OC} = (((DW_{110} - DW_{550}) / DW_{110}) / 0.33)*100$

The LOI_{OC} is the percent weight loss of the soil sediment materials at a temperature of 550°C. The DW_{105} represents the weight of the previously dried sample at 110°C before combustion at 550°C and the DW_{550} represents the weight of the sample post combustion at 550°C. Once burned, the crucibles were allowed to cool to room temperature gradually in a dessicator and were weighed again to calculate by difference the weight loss of organic matter.

To find the inorganic carbon content, the samples were returned to the furnace for 1 hour at 950°C. The previous equation for organic carbon weight loss can be modified to find inorganic carbon loss by Bengtsson and Enell's (1986) method of having the weight loss value multiplied by 1.36 instead of 0.33. The following equation represents these modifications:

$$(\text{Eq. 2.2})\ LOI_{IC} = (((DW_{550} – DW_{950}) / DW_{550})*1.36)*100$$

The LOI_{IC} is the percent weight loss of the soil sediment materials at a temperature of 950°C. The DW_{550} represents the weight of the previously dried sample post 550°C combustion but before 950°C combustion and the DW_{950} represents the weight of the sample post combustion at 950°C. The crucibles were again allowed to cool gradually to room temperature in a dessicator and were weighed once more to find by difference the loss of inorganic carbon.

To find the total LOI, a separate 2 gram aliquot of soil sample dried at 110°C was weighed and ignited in the muffle furnace at 1025°C for 1 hour. The total LOI was calculated from the following:

$$(\text{Eq. 2.3})\ LOI_{total} = ((DW_{110} – DW_{1025}) / DW_{105})*100$$

The LOI_{total} is the percent weight loss of the soil sediment materials at a temperature of 1025°C. The DW_{105} represents the weight of the previously dried sample at 110°C before combustion at 1025°C and the DW_{1025} represents the weight of the sample post combustion at 1025°C. The crucibles were again allowed to cool gradually to room temperature in a dessicator and were weighed once more to find by difference the total loss. The resulting total LOI value is a loss of organic carbon, inorganic carbon, bound water, and volatile salts (Hieri et al., 2001).

Each profile depth was analyzed three times with replicate samples in the furnace to determine reproducibility (for each organic carbon, inorganic carbon, and total LOI analysis) and an average was taken of the three plus runs until an error of less than 10% was achieved.

Major Element Analysis

Dried samples were used to prepare beads for major element analysis by x-ray fluorescence spectrometry. The samples were combusted at 1025°C for 1 hour as explained above in the total loss portion of the LOI method. This was done to remove organic material, inorganic material, and bound water. After this combustion; samples were ground with an agate mortar and pestle until a very fine particle size was achieved. An aliquot of 1 gram of sample and 10 grams of SpectroCertified Pre-Fused Fusion Flux Lithium Tetraborate ($Li_2B_4O_7$) were mixed to create the 1:10 flux ratio bead for XRF analysis.

The sample plus flux was mixed in a disposable plastic beaker with a clean stainless steel spatula to produce a homogenous mixture. The mixture was then put into a platinum crucible and loaded into a Phillips Perl’x automatic bead machine and ignited sequentially for 4 minutes at 800°C, 4 minutes at 1100°C, and 8 minutes at 1150°C to create a bead. After the sample was poured as a molten mixture into a platinum casting dish to create a homogenous bead, it was air cooled by the machine for 3 minutes. The solid glass bead was then checked for impurities and imperfections such as a mottled appearance due to bubbles, cracks running through the center of the bead, and visual specks of sample from incomplete sample dissolution. Most of the beads turned out visually perfect and were then labeled and removed for storage in a dessicator until analysis.

Results

Particle Size

Particle size analysis of the soil samples, as determined by the sieve methodology, indicate that the sample sites are generally dominated by the gravel size fraction, followed by the sand size fraction, and finally followed by the fine size fraction. The portion of the gravel size fraction and sand particle size fraction changed more with depth than did the fine size fraction. The gravel ranged from 37 to 83% of the total particle size fraction for all the cores. The average gravel fraction for all cores was 56% for all the cores. The sand fraction varies between 15 and 54% for all the cores. The average sand was 39% for all the cores. The fine fraction composed as little as 1%, and up to as much as 19 % of the total soil particle size for all the cores. The average fine size portion was 6% for all the cores.

Table 3. Soil sample particle size by weight percent at the locations and depth with bulk density per location.

Sample Name and Bulk Density (g cm^{-3})	**Sample Depth (cm)**	**Fine (%)**	**Sand (%)**	**Gravel (%)**
SC-1	(0-5)	2.5	44.1	53.4
BD = 0.72	(5-10)	2.2	31.3	66.5
	(10-15)	2.0	30.2	67.8
	(15-30)	1.3	15.3	83.3
SC-2	(0-5)	3.2	50.4	46.4
BD = 0.51	(5-10)	2.8	44.3	53.0
	(10-15)	2.2	25.0	72.8
	(15-30)	2.2	29.3	68.5
SC-3	(0-5)	3.3	51.6	45.1
BD = 0.72	(5-10)	4.0	39.6	56.4
	(10-15)	4.0	47.0	49.0
	(15-30)	2.8	31.1	66.1

SC-4	(0-5)	1.1	28.7	70.2
BD = 0.78	(5-10)	1.9	23.0	75.1
	(10-15)	2.4	21.8	75.7
	(15-30)	2.1	25.9	72.0
SC-5	(0-5)	2.6	45.6	51.8
BD = 0.28	(5-10)	3.8	39.4	56.8
	(10-15)	2.8	34.1	63.0
	(15-30)	2.9	29.6	67.4
SC-6	(0-5)	1.7	35.5	62.7
BD = 0.45	(5-10)	3.7	43.4	52.9
	(10-15)	2.4	30.6	67.0
	(15-30)	2.1	36.2	61.7
SC-7	(0-5)	8.8	54.1	37.1
BD = 0.54	(5-10)	8.8	53.2	38.0
	(10-15)	10.0	55.4	34.6
	(15-30)	9.5	50.8	39.7
SC-8	(0-5)	7.3	43.8	48.9
BD = 0.84	(5-10)	7.9	28.0	64.1
	(10-15)	10.6	49.0	40.4
	(15-30)	9.1	51.4	39.4
SC-9	(0-5)	3.3	20.4	76.3
BD = 0.36	(5-10)	4.6	18.9	76.5
	(10-15)	4.9	22.7	72.4
	(15-30)	3.5	21.1	75.5
SC-10	(0-5)	5.1	45.1	49.8
BD = 0.32	(5-10)	5.7	48.1	46.2
	(10-15)	5.2	49.4	45.4
	(15-30)	4.8	44.9	50.3
Sample Site C (Soil #1)	(0-5)	12.1	49.8	38.2
BD = 0.88	(5-10)	9.4	42.7	48.0
	(10-15)	9.0	42.9	48.0
	(15-30)	11.8	37.1	51.1
Sample Site C (Soil #2)	(0-5)	9.8	30.0	60.2
BD = 1.78	(5-10)	14.2	33.0	52.9
	(10-15)	11.6	36.6	51.8
	(15-30)	19.0	37.5	43.5

Sample Site R (Soil #1)	(0-5)	6.6	45.7	47.7
BD = 1.85	(5-10)	5.5	47.1	47.3
	(10-15)	4.8	47.2	48.0
	(15-30)	5.3	44.2	50.5
Sample Site R (Soil #2)	(0-5)	4.4	34.2	61.4
BD = 1.23	(5-10)	3.4	33.8	62.7
	(10-15)	4.2	37.6	58.2
	(15-30)	5.3	40.0	54.6
Sample Site S (Soil #1)	(0-5)	6.0	50.0	44.0
BD = 0.73	(5-10)	7.3	42.5	50.2
	(10-15)	5.6	35.4	59.0
	(15-30)	7.1	40.5	52.4
Sample Site S (Soil #2)	(0-5)	4.4	54.2	41.4
BD = 0.85	(5-10)	6.1	42.5	51.4
	(10-15)	7.1	40.4	52.5
	(15-30)	6.8	39.6	53.5

Fushan Experimental Forest

The cores from the Fushan Experiemental Forest (SC 1-6) mostly had an increase of particle size with depth. The gravel portion increased the most with depth while the sand particle size decreased the least with depth at these locations. The soil profiles exhibited higher gravel fractions and lower sand and fines fractions than most profiles of the other two sites. The fine fraction showed little change amongst the samples. Interestingly, SC-4 and SC-6 particle fractions stayed the most consistent with depth for this location (Appendix A).

Yuan-Yang Lake

Each core from Yuan-Yang Lake (SC 7-10) had fairly constant particle size with depth at each location. However, there was much more variability among the cores than at the other sites. SC-7 had the least amount of gravel (37 to 40%) while SC-9 had the highest amount of gravel (76 to 76%). SC-8 had the most variability in particle size with depth. SC-10 was fairly consistent with depth (Appendix A).

Choshui Watershed

The sample sites measured at the Choshui Watershed (SSC, SSR, SSS) showed intermediate fractions of gravel and sand particle sizes with depth compared to the other sites. No consistent particle size pattern was observed for particle size changes with depth for any of these cores. However, compared to the other two locations, there was more of the fine size fraction found here than any other location (9.8 to 19.0%).

Bulk Density

The bulk density measurements range from 0.36-1.85 g cm^{-3}. The average bulk density for the soil samples was 0.80 g cm^{-3}. Most of the samples exhibit bulk densities below 1.

Organic Carbon

The organic carbon (OC) content of the soils, as measured by loss on ignition, indicates a higher percent of carbon associated with the uppermost depths (especially the 0-5 cm depth) of the soil profiles compared to the lowermost depths in the soils of Fushan Experimental Forest and Yuan-Yang Lake. The Choshui Watershed shows little change in OC with depth. Organic carbon in the gravel particle size was only measured for the SC-4 and SC-9 sample sites. Subsequent experiments showed little difference in the OC content between broken and unbroken pieces of the gravel and sand particle sizes. The fine particle size organic carbon content of the samples was most often higher than the sand and gravel particle size organic carbon content of the samples. The fine and sand particle sizes show very similar trends with depth as they usually were separated by less than 0.2% total weight carbon contents per depth. The mean relative reproducibility for all organic carbon samples is 3% with 0% being the minimum and 28% being the maximum relative reproducibility.

Table 4. Soil sample Loss on Ignition results by weight percent at given location, depth, and particle size for Organic Carbon, Inorganic Carbon, and Total LOI.

Sample Name, Depth (cm), and Particle Size	Mean [wt%] OC (3+ runs)	Mean Relative Reproducibility (OC)	Mean [wt%] IC (3+ runs)	Mean Relative Reproducibility (IC)	Mean [wt%] LOI_{TOTAL} (1 run)
SC-1 (0-5) (fines)	8.48%	2%	2.67%	1%	27.24%
SC-1 (5-10) (fines)	4.67%	3%	2.62%	2%	13.98%
SC-1 (10-15) (fines)	2.79%	10%	2.57%	4%	8.09%
SC-1 (15-30) (fines)	2.41%	5%	1.70%	3%	0.00%
SC-1 (0-5) (sand)	7.67%	3%	3.20%	12%	
SC-1 (5-10) (sand)	3.91%	8%	3.03%	11%	
SC-1 (10-15) (sand)	2.27%	9%	2.29%	3%	
SC-1 (15-30) (sand)	1.96%	4%	2.22%	2%	
SC-2 (0-5) (fines)	6.92%	1%	1.54%	4%	

SC-2 (5-10) (fines)	3.46%	4%	1.58%	1%	
SC-2 (10-15) (fines)	2.83%	3%	1.72%	2%	
SC-2 (15-30) (fines)	1.94%	3%	2.54%	1%	
SC-2 (0-5) (sand)	5.87%	1%	2.59%	14%	
SC-2 (5-10) (sand)	2.87%	3%	2.57%	16%	
SC-2 (10-15) (sand)	2.20%	3%	2.41%	14%	
SC-2 (15-30) (sand)	1.88%	3%	2.29%	12%	
SC-3 (0-5) (fines)	5.99%	1%	2.88%	2%	
SC-3 (5-10) (fines)	4.47%	1%	1.90%	2%	
SC-3 (10-15) (fines)	4.04%	1%	1.79%	4%	
SC-3 (15-30) (fines)	3.24%	1%	1.96%	1%	
SC-3 (0-5) (sand)	5.54%	2%	2.60%	16%	
SC-3 (5-10) (sand)	4.43%	7%	2.71%	10%	
SC-3 (10-15) (sand)	3.87%	4%	2.71%	13%	
SC-3 (15-30) (sand)	3.34%	4%	2.88%	11%	
SC-4 (0-5) (fines)	9.93%	1%	3.97%	1%	
SC-4 (5-10) (fines)	4.66%	28%	4.07%	5%	
SC-4 (10-15) (fines)	3.75%	0%	4.13%	0%	
SC-4 (15-30) (fines)	4.75%	1%	3.43%	3%	
SC-4 (0-5) (sand)	11.06%	2%	3.37%	1%	
SC-4 (5-10) (sand)	4.75%	1%	3.51%	1%	
SC-4 (10-15) (sand)	3.79%	1%	3.16%	1%	
SC-4 (15-30) (sand)	4.37%	1%	3.01%	1%	
SC-4 (0-5) (gravel)	4.54%	8%	2.65%	5%	
SC-4 (5-10) (gravel)	4.18%	8%	2.12%	5%	
SC-4 (10-15) (gravel)	3.78%	3%	2.14%	3%	
SC-4 (15-30) (gravel)	3.99%	4%	2.36%	11%	
SC-5 (0-5) (fines)	9.03%	2%	2.47%	1%	29.58%
SC-5 (5-10) (fines)	5.18%	0%	2.50%	2%	14.97%
SC-5 (10-15) (fines)	4.20%	1%	3.92%	1%	13.22%
SC-5 (15-30) (fines)	4.14%	1%	3.92%	1%	12.90%
SC-5 (0-5) (sand)	8.14%	1%	3.89%	1%	
SC-5 (5-10) (sand)	4.75%	1%	2.22%	7%	
SC-5 (10-15) (sand)	4.03%	1%	2.35%	2%	
SC-5 (15-30) (sand)	3.97%	1%	2.48%	0%	
SC-6 (0-5) (fines)	7.21%	1%	2.48%	2%	20.70%

SC-6 (5-10) (fines)	5.30%	3%	2.38%	3%	13.24%
SC-6 (10-15) (fines)	3.73%	1%	2.47%	2%	10.44%
SC-6 (15-30) (fines)	3.12%	2%	2.35%	1%	7.46%
SC-6 (0-5) (sand)	6.43%	2%	2.25%	1%	
SC-6 (5-10) (sand)	4.38%	1%	2.27%	2%	
SC-6 (10-15) (sand)	3.17%	2%	2.56%	1%	
SC-6 (15-30) (sand)	2.55%	2%	2.35%	0%	
SC-7 (0-5) (fines)	2.72%	1%	1.38%	3%	8.15%
SC-7 (5-10) (fines)	2.38%	0%	1.25%	1%	7.24%
SC-7 (10-15) (fines)	2.20%	1%	1.27%	1%	6.72%
SC-7 (15-30) (fines)	2.00%	4%	1.34%	11%	6.03%
SC-7 (0-5) (sand)	1.83%	2%	0.79%	0%	
SC-7 (5-10) (sand)	1.37%	2%	0.81%	1%	
SC-7 (10-15) (sand)	1.57%	7%	0.55%	8%	
SC-7 (15-30) (sand)	1.42%	10%	0.73%	26%	
SC-8 (0-5) (fines)	1.93%	3%	2.02%	1%	
SC-8 (5-10) (fines)	1.17%	4%	2.02%	1%	
SC-8 (10-15) (fine)	1.47%	2%	2.11%	1%	
SC-8 (15-30) (fine)	1.63%	0%	0.96%	4%	
SC-8 (0-5) (sand)	1.45%	3%	0.65%	5%	
SC-8 (5-10) (sand)	0.98%	3%	0.57%	2%	
SC-8 (10-15) (sand)	1.04%	5%	1.22%	1%	
SC-8 (15-30) (sand)	0.93%	5%	1.07%	3%	
SC-9 (0-5) (fines)	5.08%	0%	1.65%	2%	18.53%
SC-9 (5-10) (fines)	2.99%	1%	1.64%	1%	10.09%
SC-9 (10-15) (fines)	2.65%	5%	1.94%	1%	8.82%
SC-9 (15-30) (fines)	2.25%	0%	2.47%	4%	7.26%
SC-9 (0-5) (sand)	6.12%	4%	1.85%	28%	
SC-9 (5-10) (sand)	3.14%	1%	1.90%	4%	
SC-9 (10-15) (sand)	2.81%	1%	1.87%	2%	
SC-9 (15-30) (sand)	2.28%	2%	2.23%	2%	
SC-9 (0-5) (gravel)	2.93%	2%	1.54%	2%	
SC-9 (5-10) (gravel)	2.34%	1%	1.76%	2%	
SC-9 (10-15) (gravel)	2.05%	1%	1.81%	1%	
SC-9 (15-30) (gravel)	1.80%	1%	2.14%	1%	
SC-10 (0-5) (fines)	4.11%	8%	1.74%	5%	9.65%

SC-10 (5-10) (fines)	3.18%	1%	1.79%	2%	8.35%
SC-10 (10-15) (fines)	3.02%	1%	1.81%	5%	8.19%
SC-10 (15-30) (fines)	2.84%	1%	1.91%	1%	8.18%
SC-10 (0-5) (sand)	3.35%	9%	1.53%	3%	
SC-10 (5-10) (sand)	2.22%	10%	1.61%	4%	
SC-10 (10-15) (sand)	2.11%	7%	1.62%	8%	
SC-10 (15-30) (sand)	2.03%	4%	1.54%	2%	
SSC (soil #1) (0-5) (fines)	1.49%	1%	1.63%	1%	
SSC (soil #1) (5-10) (fines)	1.38%	0%	1.58%	1%	
SSC (soil #1) (10-15) (fines)	1.34%	0%	1.61%	2%	
SSC (soil #1) (15-30) (fines)	1.54%	1%	1.09%	1%	
SSC (soil #1) (0-5) (sand)	0.94%	1%	0.61%	1%	
SSC (soil #1) (5-10) (sand)	0.90%	2%	0.65%	1%	
SSC (soil #1) (10-15) (sand)	0.72%	4%	1.25%	2%	
SSC (soil #1) (15-30) (sand)	0.93%	2%	1.32%	1%	
SSC (soil #2) (0-5) (fines)	1.43%	1%	1.40%	1%	3.95%
SSC (soil #2) (5-10) (fines)	1.14%	1%	1.43%	2%	2.44%
SSC (soil #2) (10-15) (fines)	1.07%	0%	1.45%	1%	3.18%
SSC (soil #2) (15-30) (fines)	0.73%	0%	1.07%	2%	2.31%
SSC (soil #2) (0-5) (sand)	1.11%	1%	1.19%	1%	
SSC (soil #2) (5-10) (sand)	0.86%	2%	1.27%	3%	
SSC (soil #2) (10-15) (sand)	0.71%	1%	1.26%	1%	
SSC (soil #2) (15-30) (sand)	0.56%	1%	1.06%	2%	
SSR (soil #1) (0-5) (fines)	1.46%	1%	1.42%	1%	
SSR (soil #1) (5-10) (fines)	1.39%	2%	1.43%	1%	
SSR (soil #1) (10-15) (fines)	1.37%	2%	1.48%	1%	
SSR (soil #1) (15-30) (fines)	1.24%	2%	1.68%	4%	
SSR (soil #1) (0-5) (sand)	0.98%	4%	1.23%	9%	
SSR (soil #1) (5-10) (sand)	0.81%	2%	1.16%	1%	
SSR (soil #1) (10-15) (sand)	0.93%	3%	0.99%	4%	
SSR (soil #1) (15-30) (sand)	0.97%	2%	1.27%	3%	
SSR (soil #2) (0-5) (fines)	1.76%	0%	2.11%	0%	5.65%
SSR (soil #2) (5-10) (fines)	1.66%	0%	2.20%	1%	5.67%
SSR (soil #2) (10-15) (fines)	1.66%	1%	1.60%	4%	5.58%
SSR (soil #2) (15-30) (fines)	1.89%	0%	1.62%	1%	6.11%
SSR (soil #2) (0-5) (sand)	1.76%	2%	1.76%	1%	

SSR (soil #2) (5-10) (sand)	1.46%	2%	1.85%	2%	
SSR (soil #2) (10-15) (sand)	1.55%	0%	1.78%	1%	
SSR (soil #2) (15-30) (sand)	1.65%	0%	1.86%	1%	
SSS (soil #1) (0-5) (fines)	3.80%	0%	2.10%	1%	11.31%
SSS (soil #1) (5-10) (fines)	2.83%	2%	2.04%	1%	8.16%
SSS (soil #1) (10-15) (fines)	2.46%	2%	2.20%	1%	7.07%
SSS (soil #1) (15-30) (fines)	1.58%	1%	1.30%	6%	4.19%
SSS (soil #1) (0-5) (sand)	3.22%	3%	1.33%	2%	
SSS (soil #1) (5-10) (sand)	1.88%	3%	0.96%	3%	
SSS (soil #1) (10-15) (sand)	1.66%	2%	1.17%	6%	
SSS (soil #1) (15-30) (sand)	1.15%	1%	0.77%	2%	
SSS (soil #2) (0-5) (fines)	1.70%	1%	3.82%	2%	14.58%
SSS (soil #2) (5-10) (fines)	1.73%	3%	4.04%	2%	7.26%
SSS (soil #2) (10-15) (fines)	1.54%	3%	4.85%	3%	7.16%
SSS (soil #2) (15-30) (fines)	1.52%	3%	4.68%	1%	6.75%
SSS (soil #2 (0-5) (sand)	3.85%	2%	2.55%	2%	
SSS (soil #2 (5-10) (sand)	1.29%	2%	4.32%	1%	
SSS (soil #2 (10-15) (sand)	1.01%	3%	5.28%	1%	
SSS (soil #2 (15-30) (sand)	1.14%	2%	4.79%	3%	

Fushan Experimental Forest

The Fushan Experimental Forest samples (SC 1-6) had higher organic carbon content than the samples from the other locations studied (Table 4). The uppermost samples from the Fushan cores exhibited large amounts of organic carbon content compared to other sample sites. Organic carbon in the Fushan samples generally decreased with depth in the core. The fine particle size fraction consistently contained more carbon than the sand particle size fraction in the uppermost depths. The fine particle size always decreased in carbon down profile, but the sand particle size slightly increased with depth for the SC-2 and SC-5 profiles. The carbon content of the gravel of SC-4 is the lowest per particle size for the profile, but it has as much as 4.54% organic carbon (Appendix B).

Yuan-Yang Lake

The Yuan-Yang Lake sample sites (SC 7-10) did not have as much organic carbon content as the Fushan Experimental Forest sites, but they did have more organic carbon content than did the Choshui Watershed sites (Table 4). The samples show a decrease of carbon with depth for all particle fractions. The organic carbon content of the gravel in SC-9 is lower than the sand and fine organic carbon content. SC-9 also had the highest organic carbon content of the samples analyzed in the area (Appendix B).

Choshui Watershed

The Choshui Watershed samples (SSC, SSR, SSS) had the least amount of organic carbon among the three sites (Table 4). The carbon content did not change much with depth. The SSS (Soil #2) site revealed patterns unlike the other core profiles of organic carbon content with depth that could possibly be associated with recent landsliding. The sand fraction displayed much higher content values for the 0-5 cm depth than the fines. (Appendix B).

Inorganic Carbon

The inorganic carbonate (IC) measured by Loss on Ignition indicates a higher percent of carbon associated with the uppermost depths (especially the 0-5 cm depth) of the soil profiles than the lowermost depths in the Fushan Experimental Forest and Yuan-Yang Lake. The Choshui Watershed shows little change in IC with depth. The percent inorganic carbon content is less than the organic carbon content in most of the profiles. Inorganic carbon in the gravel particle size was only measured for the SC-4 and SC-9 sample sites. The inorganic carbon concentrations in the gravel size fractions measured were low and relatively constant with depth, ranging from 1.64–2.65% carbon in the gravels. Subsequent experiments showed little difference in the IC content between broken and unbroken pieces of the gravel and sand particle sizes. The fine particle size organic carbon content is most often higher than were the sand and gravel particle size organic carbon content. The fine and sand particle sizes show very similar trends with depth as they are separated by less than 0.2% total weight carbon contents per depth. The mean relative reproducibility for all inorganic carbon samples is 3% with 0% being the minimum and 28% being the maximum relative reproducibility.

Fushan Experimental Forest

The Fushan Experimental Forest (SC 1-6) samples had the highest inorganic carbon content among the three locations except for the SSS (Soil #2) profile of the Choshui Watershed (Table 4). Fine and sand particle sizes traded dominance in carbon content amongst them. The inorganic carbon content of the SC-4 profile was the lowest amount of carbon content for that profile (Appendix B).

Yuan-Yang Lake

The Yuan-Yang Lake (SC 7-10) sample sites were not the highest or lowest inorganic carbon content sites (Table 4). They were fairly constant with depth. The SC-9 gravel inorganic carbon content was very close to the sand and fine inorganic carbon contents of that site (Appendix B).

Choshui Watershed

The Choshui Watershed (SSC, SSR, SSS) sample sites had the least amount of inorganic carbon compared to the other two sites (Table 4). Except for the SSS (Soil #2) site, the carbon content did not vary much with depth. The SSS (Soil #2) site revealed patterns unlike the other core profiles of inorganic carbon content with depth. The fine and sand particle sizes showed an inorganic carbon content that was much larger than the organic content for the same profile (Appendix B).

Total Loss on Ignition

The total LOI (LOI_{total}) was measured only for the fine particle size portion of a few samples. The measured samples for total carbon are the same samples measured for major oxides.

Fushan Experimental Forest

The Fushan Experimental Forest (SC 1-6) sites had the highest amount of LOI_{total} of the three locations with as much as 29.6% (Table 4). SC-5 had the highest LOI_{total} of the samples measured (Appendix B).

Yuan-Yang Lake

The Yuan-Yang Lake (SC-7-10) sites had less LOI_{total} than the Fushan Experimental Forest sites, but more than the Choshui Watershed sites (Table 4). SC-9 had the most LOI_{total} of the samples measured for this location (Appendix B).

Choshui Watershed

The Choshui Watershed (SSC, SSR, SSS) sites had the least LOI_{total} of the three locations (Table 4). The least LOI_{total} measured for this location was in SSC (Soil #2), which consistently had less than 4% LOI_{total} (Appendix B).

Major Oxides

SiO_2 represents nearly half of the elemental composition in these soils. Al_2O_3 is the second most dominant oxide except for in SC-6. CaO and MgO are the lowest oxides when compared to the other elements analyzed by XRF (Table 5).

Table 5. Elemental results for major elements analyzed by XRF.

Sample Name and Depth (cm)	**SiO_2 (%)**	**TiO_2 (%)**	**Al_2O_3 (%)**	**Fe_2O_3 (%)**	**MnO (%)**	**MgO (%)**	**CaO (%)**	**Na_2O (%)**	**K_2O (%)**	**P_2O_5 (%)**	**Total Majors (%)**
SC-1 (0-5)	44.55	0.68	15.89	6.08	1.15	0.06	0.01	0.44	2.42	0.18	71.46
SC-1 (5-10)	47.15	0.73	17.67	7.50	1.44	0.07	0.00	0.33	2.57	0.12	77.58
SC-1(10-15)	54.50	0.85	20.09	8.08	1.85	0.07	0.00	0.39	3.20	0.11	89.13
SC-1(15-30)	58.72	0.88	21.52	8.33	2.19	0.12	0.00	0.43	3.72	0.11	96.03
SC-5 (0-5)	45.81	0.89	16.27	6.97	0.69	0.01	0.03	0.38	1.95	0.14	73.12
SC-5 (5-10)	53.16	1.04	19.31	8.54	0.82	0.02	0.00	0.38	2.29	0.09	85.65
SC-5 (10-15)	54.57	1.07	20.15	8.86	0.92	0.02	0.00	0.37	2.39	0.08	88.43
SC-5 (15-30)	54.52	1.06	20.25	8.80	1.05	0.02	0.00	0.36	2.41	0.08	88.55
SC-6 (0-5)	50.52	0.98	0.41	2.73	1.07	0.03	0.00	0.41	2.73	0.26	59.14
SC-6 (5-10)	54.98	1.04	0.38	3.01	1.28	0.03	0.00	0.38	3.01	0.19	64.31
SC-6 (10-15)	56.79	1.06	0.36	3.12	1.36	0.03	0.00	0.36	3.12	0.15	66.37
SC-6 (15-30)	58.83	0.95	0.35	3.33	1.66	0.04	0.00	0.35	3.33	0.11	68.96
SC-1 FUSHAN (Gordon, 2006)	59.7	0.851	19.8	7.56	0.02	2.5	0.00	0.49	3.54	0.12	94.5
SC-1 (Gordon, 2006)	84.0	0.320	7.95	2.19	0.056	0.409	0.098	0.56	1.93	0.061	97.5
SC-5 (Gordon, 2006)	85.2	0.317	7.28	2.00	0.048	0.473	0.131	0.62	1.59	0.055	97.7
SC-7 (0-5)	64.21	0.95	15.87	3.32	0.38	0.01	0.00	0.25	4.29	0.12	89.39
SC-7 (5-10)	65.20	0.98	16.45	3.48	0.39	0.01	0.00	0.26	4.44	0.11	91.32
SC-7 (10-15)	63.71	0.98	16.85	3.45	0.39	0.01	0.00	0.26	4.49	0.10	90.25
SC-7 (15-30)	61.97	1.02	18.46	3.57	0.43	0.01	0.00	0.27	4.98	0.10	90.81
SC-9 (0-5)	52.52	0.66	11.92	2.87	0.34	0.01	0.00	0.32	2.65	0.13	71.42
SC-9 (5-10)	59.93	0.78	14.78	3.94	0.44	0.01	0.00	0.38	3.20	0.11	83.56
SC-9 (10-15)	56.20	0.75	14.83	5.09	0.51	0.01	0.00	0.35	3.05	0.09	80.88
SC-9 (15-30)	57.27	0.79	16.17	3.94	0.47	0.01	0.00	0.37	3.18	0.07	82.28
SC-10 (0-5)	63.43	0.63	14.28	3.74	0.51	0.04	0.05	0.53	3.16	0.09	86.46
SC-10 (5-10)	60.91	0.80	16.24	4.68	0.52	0.04	0.00	0.51	3.74	0.11	87.55
SC-10 (10-15)	60.92	0.81	16.21	4.70	0.50	0.05	0.00	0.47	3.75	0.11	87.53
SC-10 (15-30)	57.86	0.79	15.88	4.53	0.47	0.04	0.00	0.43	3.72	0.11	83.83
SC-10	89.6	0.11	4.91	0.316	0.004	0.11	0	0.034	1.53	0.019	96.7

(Gordon, 2006)										
YYL STREAM#2 (Gordon, 2006)	92.3	0.07	4.25	0.530	0.007	0.13	0	0.039	0.89	0.014	98.2
SSC#2 (0-5)	63.30	0.59	9.62	3.73	1.08	0.05	0.35	2.11	1.82	0.10	82.74
SSC#2 (5-10)	62.28	0.61	10.25	4.04	1.23	0.06	0.43	2.17	1.81	0.11	82.99
SSC#2 (10-15)	64.11	0.65	10.66	4.30	1.28	0.07	0.52	2.31	1.88	0.11	85.88
SSC#2 (15-30)	66.58	0.42	7.36	3.30	0.88	0.07	0.32	1.61	1.51	0.08	82.13
SSR#2 (0-5)	63.28	0.77	15.02	5.08	0.83	0.08	0.11	0.87	2.67	0.12	88.83
SSR#2 (5-10)	64.16	0.77	16.07	5.33	0.83	0.07	0.06	0.83	2.87	0.11	91.10
SSR#2 (10-15)	64.25	0.79	16.85	5.71	0.84	0.06	0.03	0.82	3.01	0.11	92.46
SSR#2 (15-30)	51.80	0.64	13.72	4.62	0.70	0.05	0.03	0.66	2.45	0.09	74.76
SSS#1 (0-5)	56.44	0.59	9.17	5.00	1.64	0.09	1.14	1.84	2.05	0.20	78.16
SSS#1 (5-10)	63.08	0.69	10.64	6.10	1.92	0.10	1.04	2.06	2.30	0.21	88.14
SSS#1 (10-15)	65.00	0.72	11.25	6.32	2.02	0.11	1.13	2.12	2.34	0.21	91.20
SSS#1 (15-30)	61.97	0.66	10.20	5.63	1.90	0.09	0.65	2.06	1.98	0.15	85.30
SSS#2 (0-5)	41.88	0.48	10.63	4.30	1.28	0.05	0.92	1.55	1.91	0.12	63.14
SSS#2 (5-10)	53.09	0.69	16.15	6.17	1.76	0.08	2.28	1.83	2.90	0.12	85.07
SSS#2 (10-15)	51.83	0.69	16.37	6.24	1.77	0.08	3.05	1.78	2.93	0.11	84.86
SSS#2 (15-30)	52.21	0.69	16.31	6.24	1.77	0.08	2.85	1.81	2.92	0.11	84.99
SAMPLE SITE R (Gordon, 2006)	80.4	0.33	9.98	2.79	0.078	0.22	0	0.386	2.95	0.079	97.2
WATERSHED (Gordon, 2006)	79.3	0.56	9.63	3.27	0.081	0.88	0.295	1.25	1.95	0.092	97.3

Major element analysis by XRF of bedrock samples collected near my soil samples (Gordon, 2006) are included in Table 5 for comparison to the soil samples.

Discussion

Chemical Index of Alteration

The Chemical Index of Alteration (CIA*) provides a relative measure of chemical weathering at the sites (Table 6, Table 7, and Table 8). It represents the preferential weathering of the soluble elements sodium and potassium from the sample soils. The CIA* value is calculated as the following (Nesbitt and Young, 1982) and which was modified by Colin et al. (1999):

$$\text{(Eq. 3)}\ CIA^* = \left[\frac{Al_2O_3}{Al_2O_3 + Na_2O + K_2O}\right] * 100$$

Na and K both have a +1 charge and Al has a +3 charge. Since the Na^{+1} and K^{+1} are more soluble than the Al^{+3}, they will be weathered, leaving the Al^{+3} behind. Therefore, the higher CIA* values correspond with a greater amount of chemical weathering experienced by the soils since the soils will preferentially lose the soluble elements Na and K.

The CIA* values were all calculated using only the fine size particle size elemental data from the XRF and these values were compared to the average rock CIA* values in Gordon, 2006 (Table 6, Table 7, Table 8). The average rock values from Gordon’s thesis plotted in Appendix C represent the average rock value per location (Table 5). The soil CIA* and the average rock CIA* values for each location were plotted together (Appendix C).

The CIA* values for the Fushan Experimental Forest soils are much higher than the other soils, indicating that it is the most chemically weathered of the three locations (Table 6). The Fushan soils have higher CIA* values than the average Fushan rock CIA* value, indicating they are more chemically weathered than the rock. Yuan-Yang Lake's CIA* is similar to the average Yuan-Yang Lake rock CIA* value, therefore showing little chemical weathering (Table 7). The soil CIA* values for the Choshui Watershed have a much greater variability than do the soil CIA* values of the other sites (Table 8). Compared to the other two sites, the Choshui Watershed samples are not so chemically weathered.

Fushan Experimental Forest

The Fushan Experiemental Forest (SC 1-6) samples all have higher CIA*s compared to the average rock CIA* of the area (Table 6). The area is highly chemically weathered with SC-5 being the highest with a CIA* value around 87.

Yuan-Yang Lake

The Yuan-Yang Lake (SC 7-10) samples all have CIA* values similar to the average rock CIA* of the area indicating little weathering (Table 7). The average rock CIA* is 79 for this location.

Choshui Watershed

The Choshui Watershed (SSC, SSR, SSS) soil samples have CIA* values above and below the average rock CIA* value of 75 for the area (Table 8). Of the soil samples at this location, the highest CIA* value is for SSR (Soil #2) at 81.52 and the lowest CIA* value is for SSS (Soil #1) at 70.21. These values indicate variable weathering of the soils in the location.

Table 6. Fushan Experimental Forest

Rock Samples (Gordon, 2006)	**Rock Type**		**Al_2O_3**	**Na_2O**	**K_2O**	**CIA***
SC-1 FUSHAN	Sedimentary	shale	19.8	0.49	3.54	83.10
SC-2	Sed to light metamorphic	shale (harder)	19.5	0.51	3.44	83.15
SC-3	Sed to light metamorphic	shale	20.7	0.22	3.79	83.78
SC-1	Sedimentary		7.95	0.56	1.93	76.16
SC-5	Sedimentary	shale	7.28	0.62	1.59	76.74
					Mean	80.58

XRF Soil Samples	**Al_2O_3**	**Na_2O**	**K_2O**	**CIA***
SC-1 (0-5 cm)	15.89	0.44	2.42	84.75
SC-1 (5-10 cm)	17.67	0.33	2.57	85.87
SC-1(10-15 cm)	20.09	0.39	3.20	84.86
SC-1(15-30 cm)	21.52	0.43	3.72	83.81
SC-5 (0-5 cm)	16.27	0.38	1.95	87.51
SC-5 (5-10 cm)	19.31	0.38	2.29	87.85
SC-5 (10-15 cm)	20.15	0.37	2.39	87.94
SC-5 (15-30 cm)	20.25	0.36	2.41	87.96
SC-6 (0-5 cm)	18.16	0.41	2.73	85.26
SC-6 (5-10 cm)	19.55	0.38	3.01	85.21
SC-6 (10-15 cm)	20.33	0.36	3.12	85.37
SC-6 (15-30 cm)	20.27	0.35	3.33	84.64

Depth of Soil Samples	**Mean Soil CIA***
(0-5 cm)	85.84
(5-10 cm)	86.31
(10-15 cm)	86.05
(15-30 cm)	85.47
Total (0-30 cm)	85.92

Table 7. Yuan-Yang Lake

Rock Samples (Gordon, 2006)	**Rock Type**		**Al_2O_3**	**Na_2O**	**K_2O**	**CIA***
SC-10	dark rock - block rod clasts	no layers	4.91	0.03	1.53	75.84
YYL STREAM #2	Sed to light metamorphic	quartzose sandstone	4.25	0.04	0.89	82.07
					Mean	**78.95**

XRF Soil Samples	**Al_2O_3**	**Na_2O**	**K_2O**	**CIA***
SC-7 (0-5 cm)	15.87	0.25	4.29	77.75
SC-7 (5-10 cm)	16.45	0.26	4.44	77.78
SC-7 (10-15 cm)	16.85	0.26	4.49	78.02
SC-7 (15-30 cm)	18.25	0.26	4.90	77.97
SC-9 (0-5 cm)	11.92	0.32	2.65	80.06
SC-9 (5-10 cm)	14.78	0.38	3.20	80.49
SC-9 (10-15 cm)	14.83	0.35	3.05	81.37
SC-9 (15-30 cm)	16.17	0.37	3.18	82.01
SC-10 (0-5 cm)	14.28	0.53	3.16	79.49
SC-10 (5-10 cm)	16.24	0.51	3.74	79.23
SC-10 (10-15 cm)	16.21	0.47	3.75	79.32
SC-10 (15-30 cm)	15.88	0.43	3.72	79.28

Depth	**Mean Soil CIA***
(0-5 cm)	78.77
(5-10 cm)	78.79
(10-15 cm)	79.17
(15-30 cm)	79.28
Average	79.00

Table 8. Choshui Watershed

Rock Samples (Gordon, 2006)	**Rock Type**	**Al_2O_3**	**Na_2O**	**K_2O**	**CIA***
SAMPLE SITE R	sandstone	9.98	0.39	2.95	74.95
WATERSHED	sandy mudstone	9.63	1.25	1.95	75.06
				Mean	**75.00**

XRF Soil Samples	**Al_2O_3**	**Na_2O**	**K_2O**	**CIA***
SSS#1 (0-5 cm)	9.17	1.84	2.05	70.21
SSS#1 (5-10 cm)	10.64	2.06	2.30	70.97
SSS#1 (10-15 cm)	11.25	2.12	2.34	71.61
SSS#1 (15-30 cm)	10.20	2.06	1.98	71.61
SSS#2 (0-5 cm)	10.63	1.55	1.91	75.42
SSS#2 (5-10 cm)	16.15	1.83	2.90	77.33
SSS#2 (10-15 cm)	16.37	1.78	2.93	77.64
SSS#2 (15-30 cm)	16.31	1.81	2.92	77.55
SSC#2 (0-5 cm)	9.62	2.11	1.82	71.00
SSC#2 (5-10 cm)	10.25	2.17	1.81	72.00
SSC#2 (10-15 cm)	10.66	2.31	1.88	71.79
SSC#2 (15-30 cm)	7.36	1.61	1.51	70.23
SSR#2 (0-5 cm)	15.02	0.87	2.67	80.91
SSR#2 (5-10 cm)	16.07	0.83	2.87	81.31
SSR#2 (10-15 cm)	16.85	0.82	3.01	81.50
SSR#2 (15-30 cm)	13.72	0.66	2.45	81.52

Depth	**Mean Soil CIA***
(0-5 cm)	74.39
(5-10 cm)	75.40
(10-15 cm)	75.64
(15-30 cm)	75.23
Average	75.16

Erosional Factors

All the soils are predominately composed of larger size fractions, with little clay, and with very low concentrations of carbonate and organic carbon. This observation, along with CIA* results, suggests that soils have not experienced extensive chemical weathering, but they have experienced substantial physical weathering. However, as evident from the previous studies in the area (Lyons et al., 2005; Carey et al., 2005: Goldsmith et al., 2008) the rapid uplift and erosion rates remove the more weathered material, exposing fresh rock that is rapidly chemically weathered. Spatial variation and heterogeneity among the soils in a given location could be influenced by slight erosional factor variations, differences in vegetation, proximity to water features, or even differences in the underlying bedrock lithologies.

1. Uplift

The two central sites, Fushan Experimental Forest and Yuan-Yang Lake, experience a greater amount of uplift than the western site, the Choshui Watershed, and hence have steeper hillside slopes because of this (Table 2). The steeper slopes allow for more landsliding and mass wasting due to physical erosion (Roering et al., 2007).

2. Lithology

A range of lithologies on Taiwan, due to the island's uplift and erosion, can account for substantial differences in the weathering of the soils. The western location, Choshui

Watershed had a much more friable sedimentary lithology than the central locations Fushan Experimental Forest and Yuan-Yang Lake which have much more metamorphic lithologies. However, the Choshui Watershed and the Yuan-Yang Lake soils experienced similar amounts of erosion (Table 1).

3. Rainwater Runoff

Precipitation on Taiwan is an important control on erosion. Typhoons hit the island an average of four times a year and create muddy hyperpycnal flows in the streams of Taiwan, particularly in the streams with the highest sediment discharges over the years (Goldsmith et al., 2008). Typhoons also result in large dissolved fluxes. Typhoon Mindulle's storm flux in 2004 for the Choshui Watershed alone was equivalent to the 31% annual CO_2 consumption of small mountainous rivers in the North and South Islands of New Zealand (Goldsmith et al., 2008). This indicates the importance of episodic storm events to chemical weathering.

4. Seismicity

Due to the convergent plate boundary beneath Taiwan, the island experiences many seismic events. Many faults such as the Chelunpu fault that is associated with the 1990 Chi Chi earthquake (Jian-Cheng Lee and Yu-Chang Chan, 2007) run north-south in the western area of Taiwan. Sample site SSR was in the closest proximity to the Chi Chi earthquake. Locations SSC and SSS, which are predominately mudstone lithology, were collected in the area that experienced the most landsliding after the Chi Chi earthquake among the six sampling locations in the Choshui Watershed. The Choshui Watershed experienced the largest amount of landsliding of the three locations due to its proximity to the Chelungpu fault.

Fushan Experimental Forest

The Fushan Experimental Forest site exhibits soil profiles closest to what would be expected in less erosive settings. This site had the highest organic carbon content indicating the most well developed soils. This suggests the limited role of runoff as an erosional mechanism for this setting.

Yuan-Yang Lake

The Yuan-Yang Lake soil samples were collected at the highest elevations (1712-1718 m) and steepest slopes (as high as 60%) for this study (Table 2). The high rates of uplift at the Yuan-Yang Lake site contribute to the creation of steeper slopes and less developed soils. These elevational and slope factors account for the lower organic carbon content here, compared to the Fushan site.

Choshui Watershed

Lithology and seismicity in the Choshui watershed result in soil profiles very similar to those of Yuan-Yang Lake site. These results indicate different factors can result in similar soil organic carbon profiles for different locations. These results are consistent with Kao and Milliman's (2009) identification of varying physical erosion parameters throughout the island. The organic carbon results are consistent with observations in the Liwu watershed in eastern Taiwan by Hilton et. al. (2008).

CIA* profile SSR (Soil #2) has the highest values, indicating the most weathered soils (Table 6; Appendix C). Of the Choshui Watershed cores, this location was the closest to the Chelungpu fault, had the highest elevation, and was on the steepest slope (Table 2). However, this location experienced less landsliding after the earthquake than did the other Choshui core locations (S.-J. Kao, personal communication). Possible reasons for the limited landsliding in this location include a more competent bedrock, loss of readily removed material in previous landslides, more vegetation, or unknown factors.

All the other Choshui cores were in regions that experienced some degree of landsliding after the Chi Chi earthquake. This landsliding may have removed weathered material resulting in the lower CIA* values observed (Table 6; Appendix C).

Conclusions

The soils on Taiwan have experienced much physical and chemical weathering compared to the underlying bedrock. The soils contain more gravel than any other particle size measured, have LOI profiles with limited development, and have some CIA values that are greater than the bedrock. The physical weathering experienced by the soils is quite large considering the limited development among the soil profiles.

The particle size of the samples, carbon contents in the soil samples, and the CIA* values of the Taiwan locations with different lithology and seismicity along with varying rates of uplift, runoff, and erosion exhibit similar soil profiles even though they have experienced different erosional factors. Even though the Choshui Watershed is more affected by frequent seismicity and has a weak lithology, it has similar profiles as the Yuan-Yang Lake soil profiles which are more affected by intense uplift. The soil profiles in areas where these erosional factors play a limited role are more developed as evident in the Fushan Experimental Forest sites. The Fushan Experimental Forest has experienced the most chemical weathering, but possibly the least physical weathering due to its more mature soil profiles, stronger lithology, and limited seismicity.

Taiwan’s steep slopes coupled with lithology, seismicity, and episodic storm events greatly increase physical mass wasting and chemical weathering of these soils. These erosional factors are considered the main controls on soil development and carbon storage on the island.

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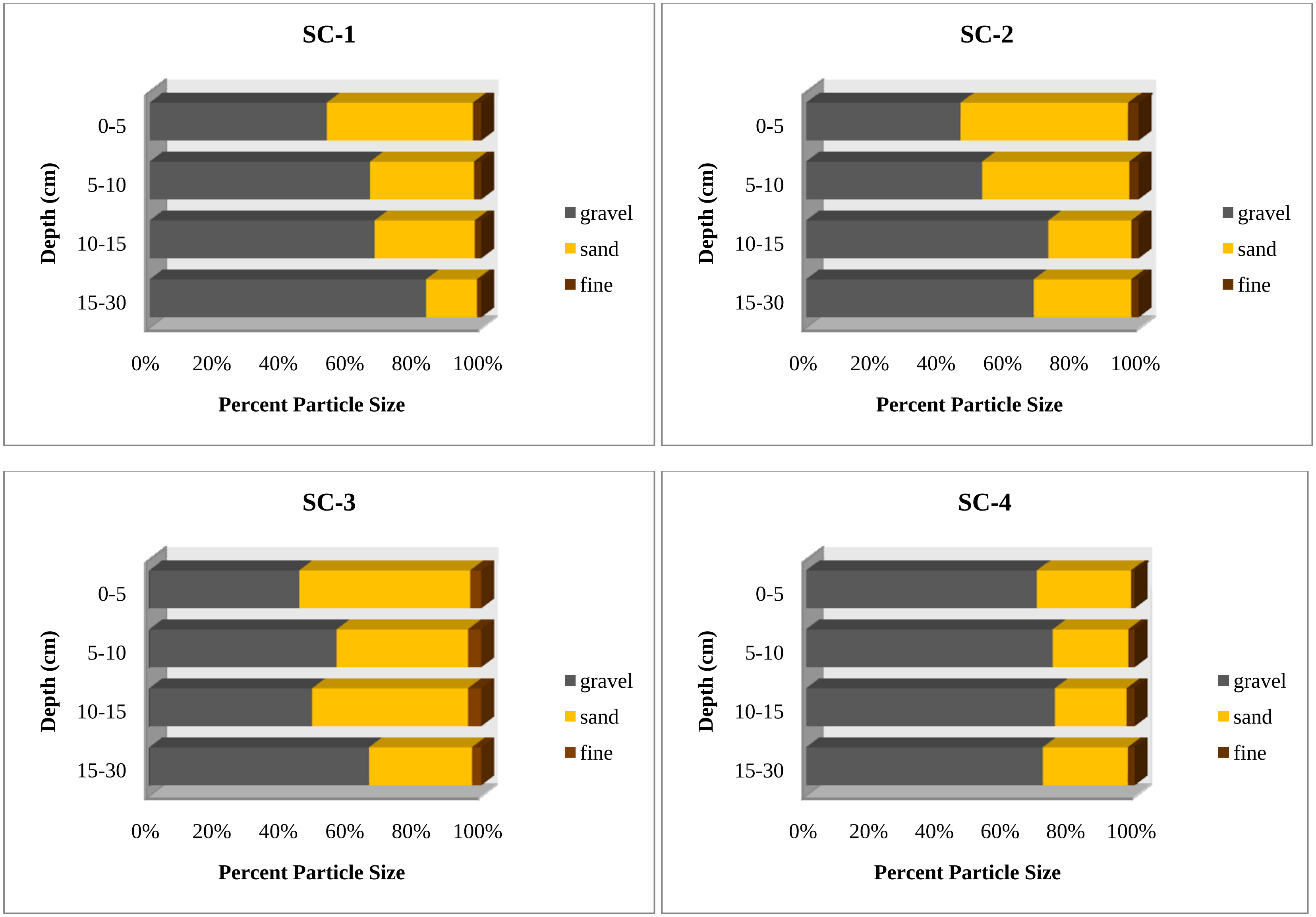
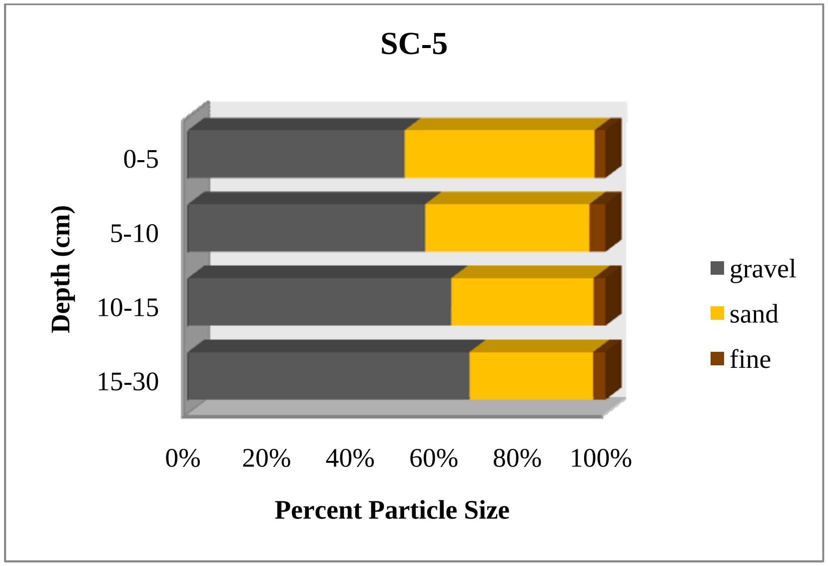
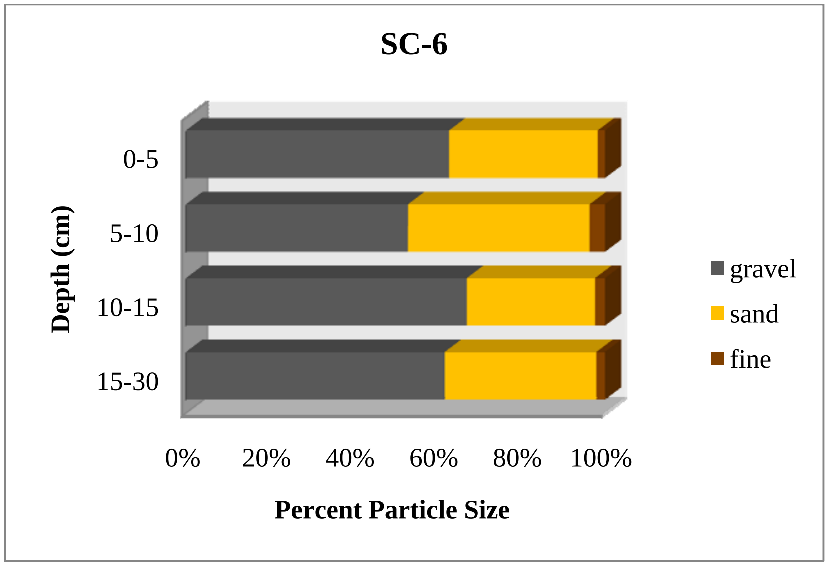
Appendix A

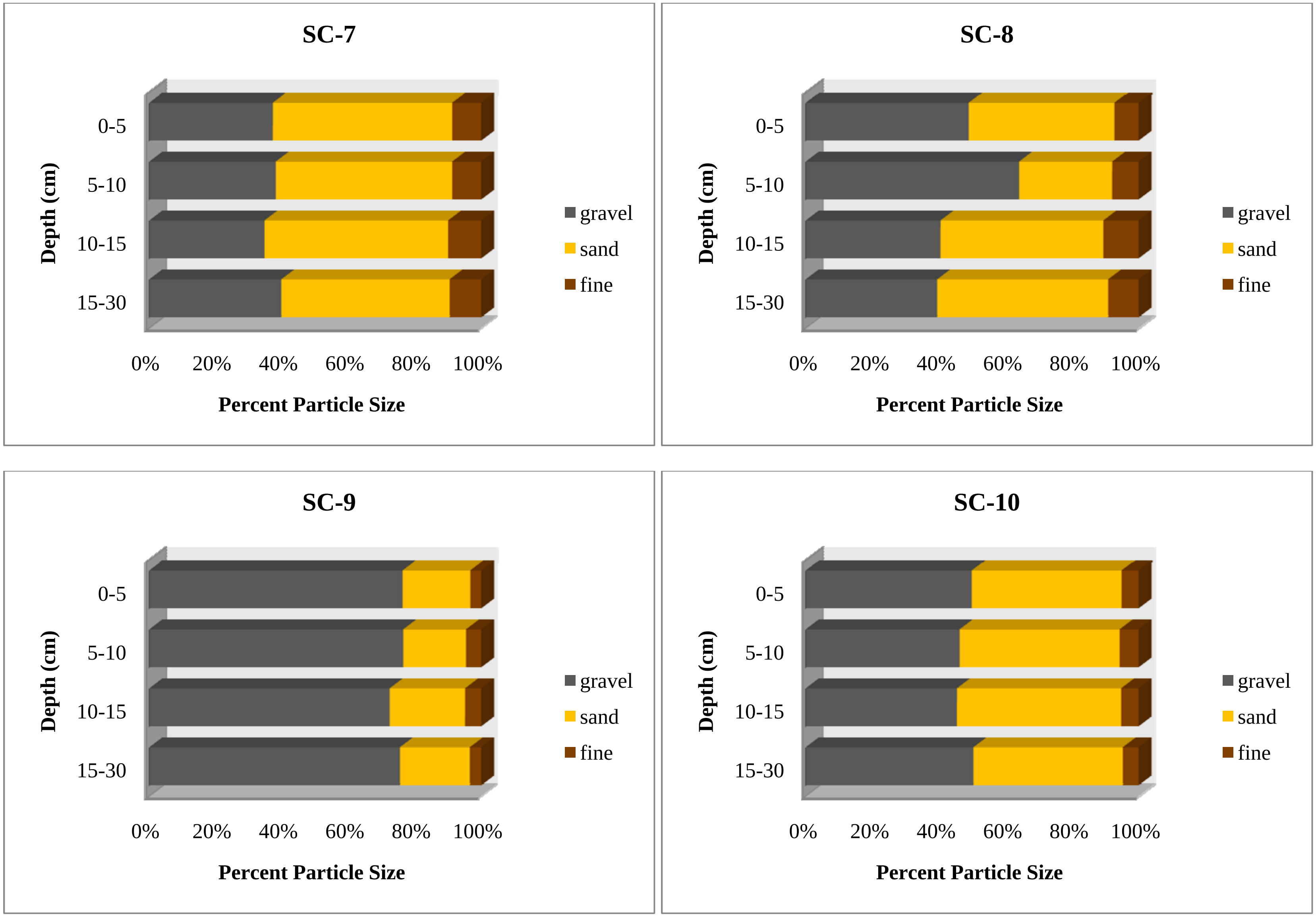
Fushan Experimental Forest Particle Size



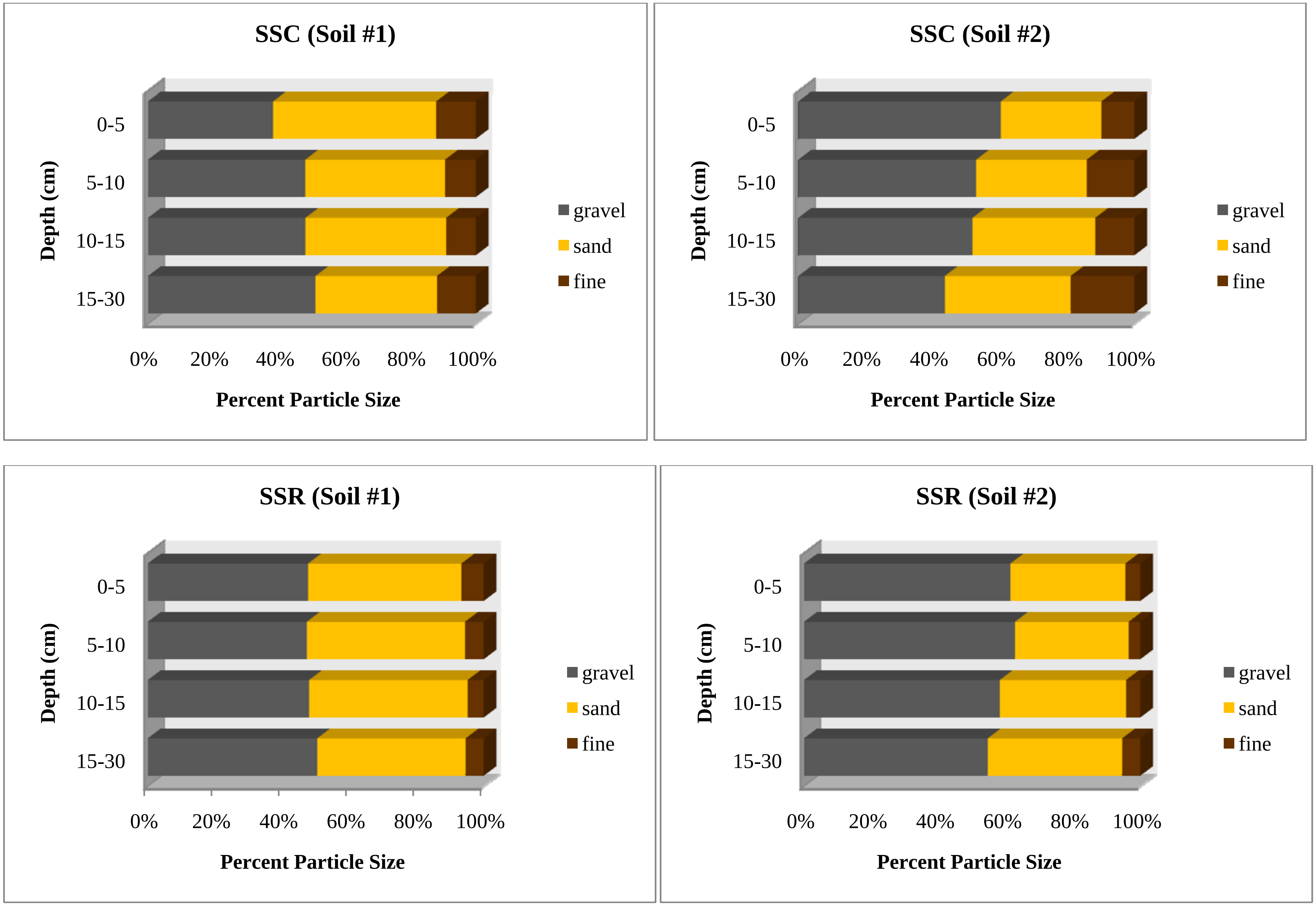

SC-5
Depth (cm)
0-5
5-10
10-15
15-30
0%
20%
40%
60%
80%
100%
Percent Particle Size
gravel
sand
fine

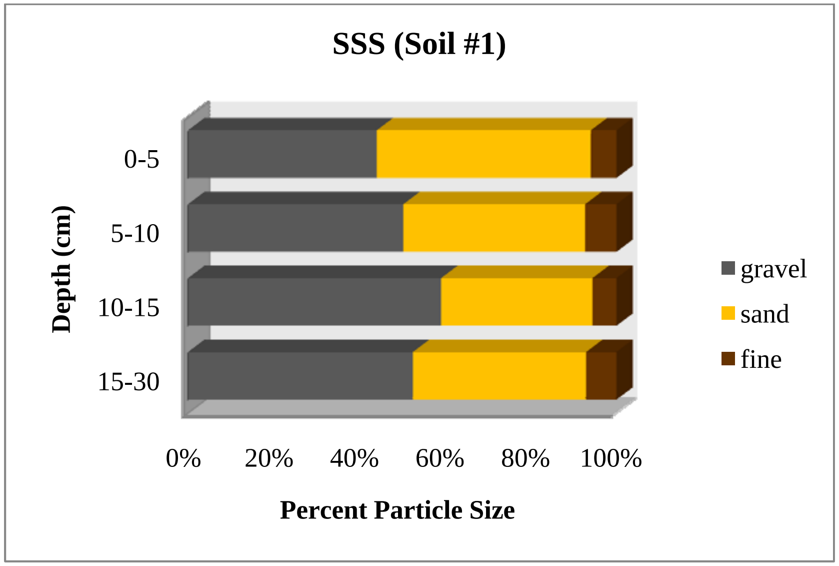

SC-6
Depth (cm)
0-5
5-10
10-15
15-30
0%
20%
40%
60%
80%
100%
Percent Particle Size
gravel
sand
fine

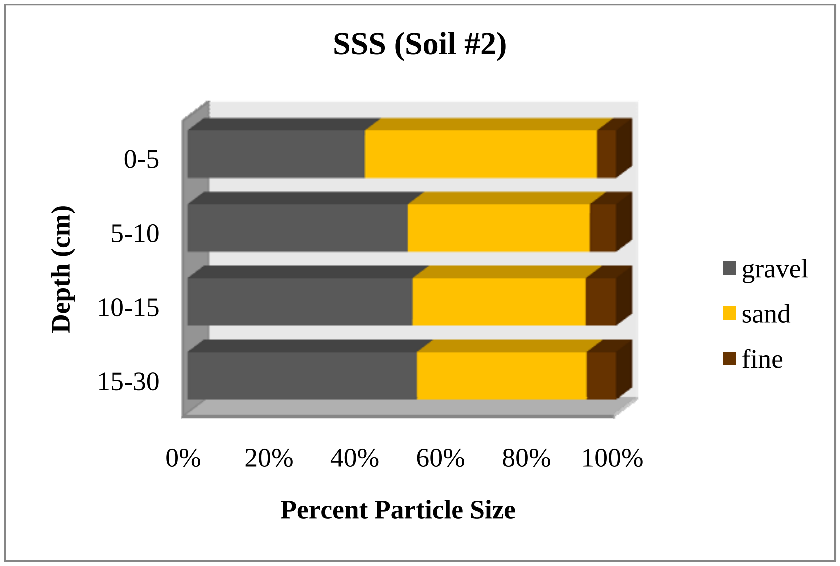
Yuan-Yang Lake Particle Size



Choshui Watershed Particle Size




SSS (Soil #1)
Depth (cm)
0-5
5-10
10-15
15-30
0%
20%
40%
60%
80%
100%
Percent Particle Size
gravel
sand
fine


SSS (Soil #2)
Depth (cm)
0-5
5-10
10-15
15-30
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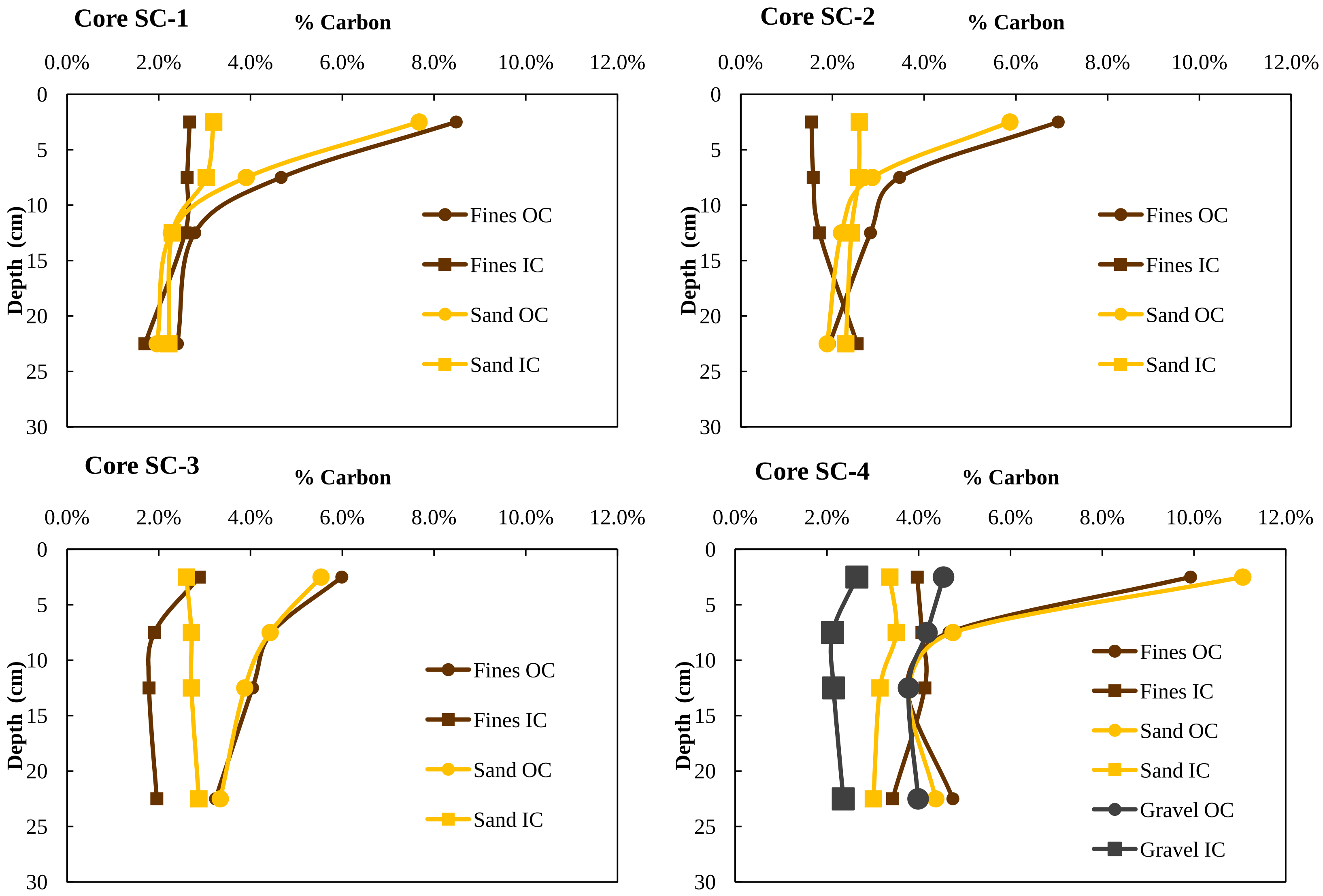
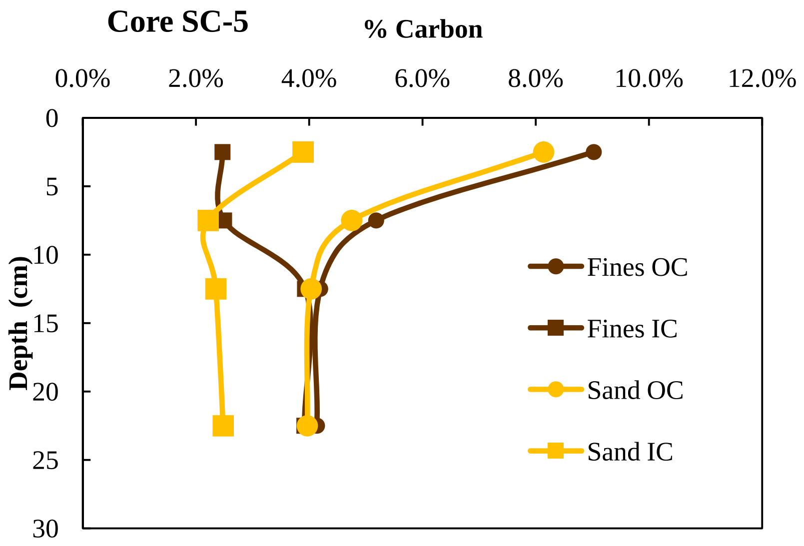
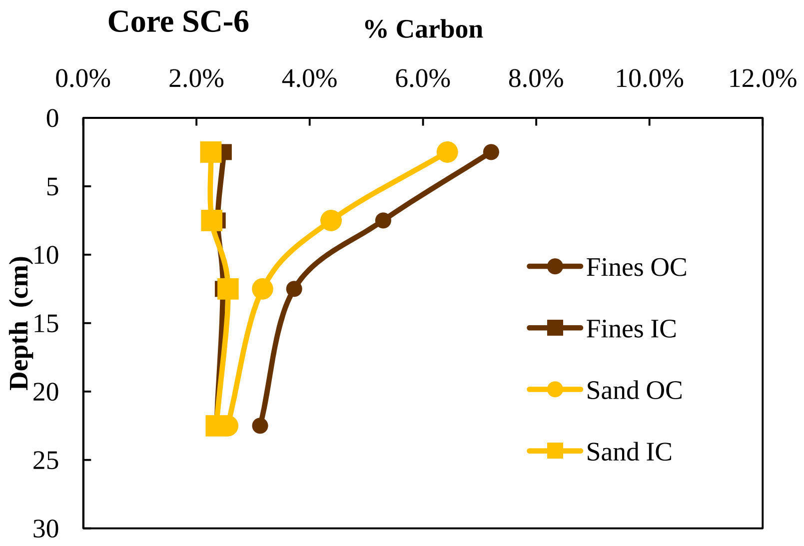
20%
40%
60%
80%
100%
Percent Particle Size
gravel
sand
fine

Appendix B

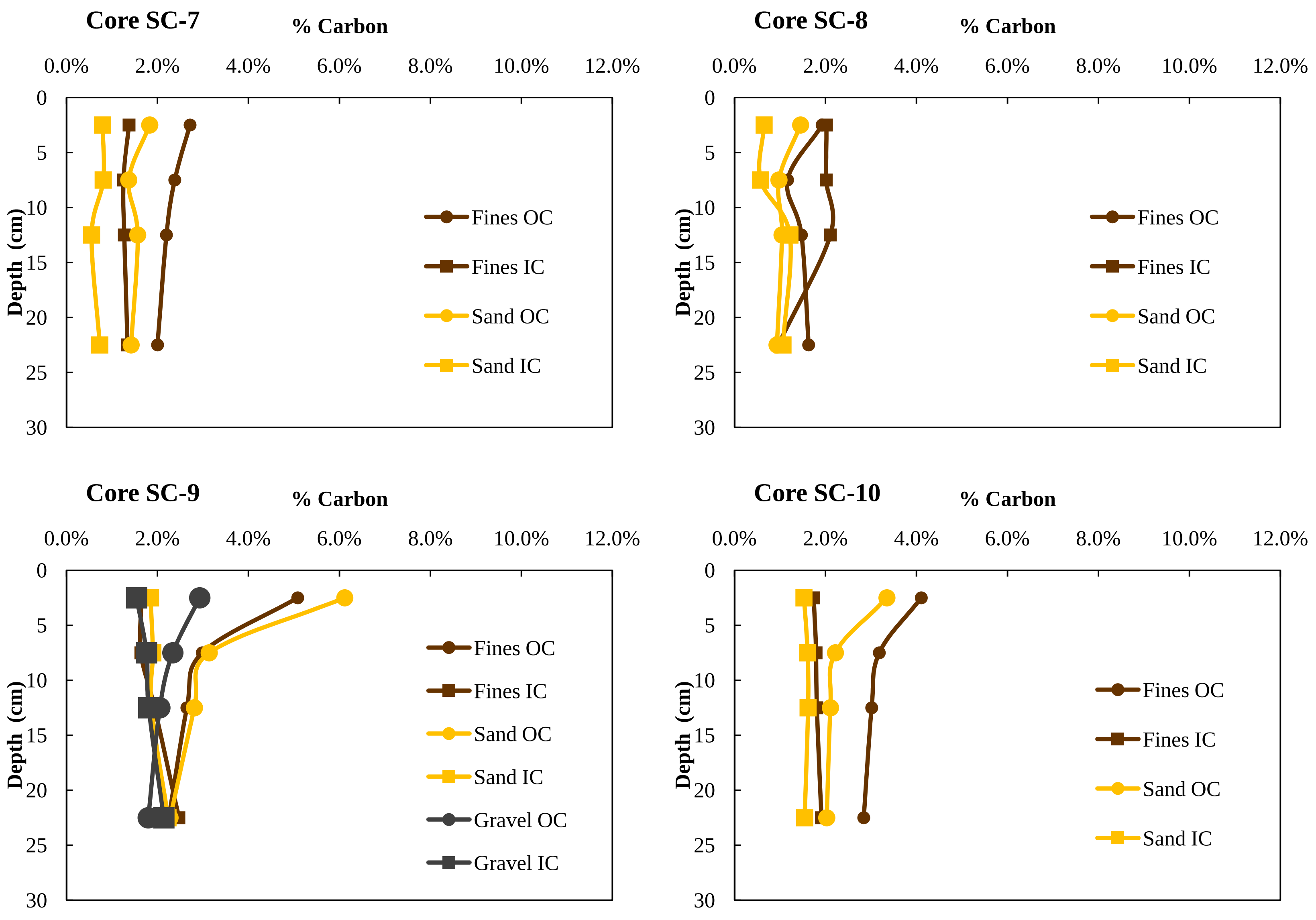
Fushan Experimental Forest Loss on Ignition



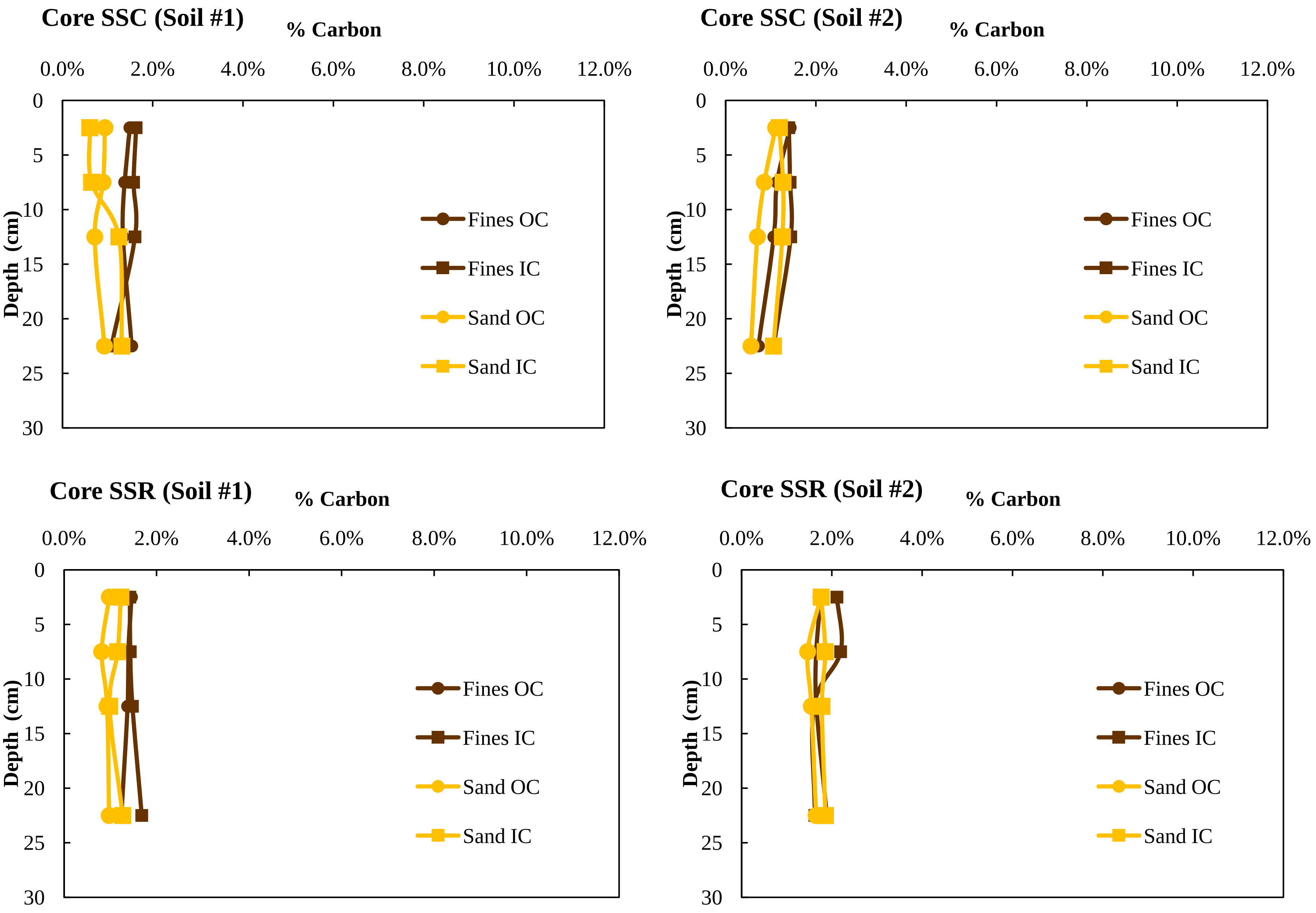

Core SC-5
% Carbon
0.0%
2.0%
4.0%
6.0%
8.0%
10.0%
12.0%
Depth (cm)
0
5
10
15
20
25
30
Fines OC
Fines IC
Sand OC
Sand IC

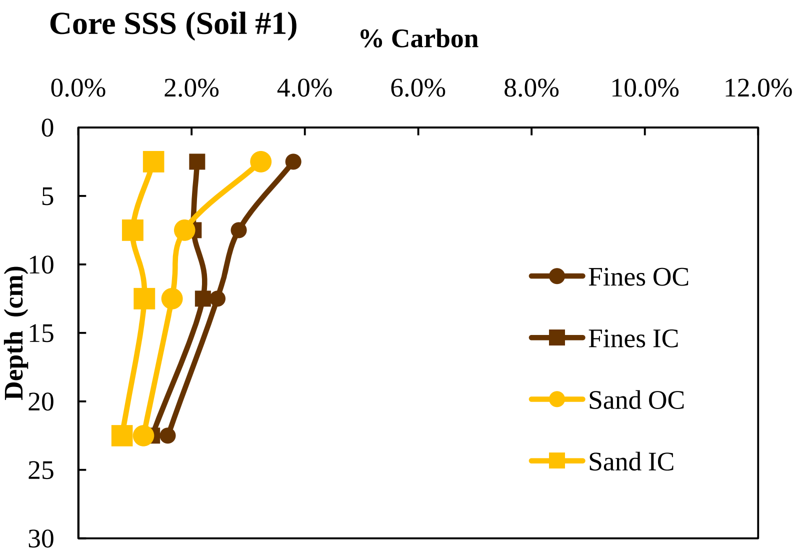

Core SC-6
% Carbon
0.0%
2.0%
4.0%
6.0%
8.0%
10.0%
12.0%
Depth (cm)
0
5
10
15
20
25
30
Fines OC
Fines IC
Sand OC
Sand IC

Yuan-Yang Lake Loss on Ignition

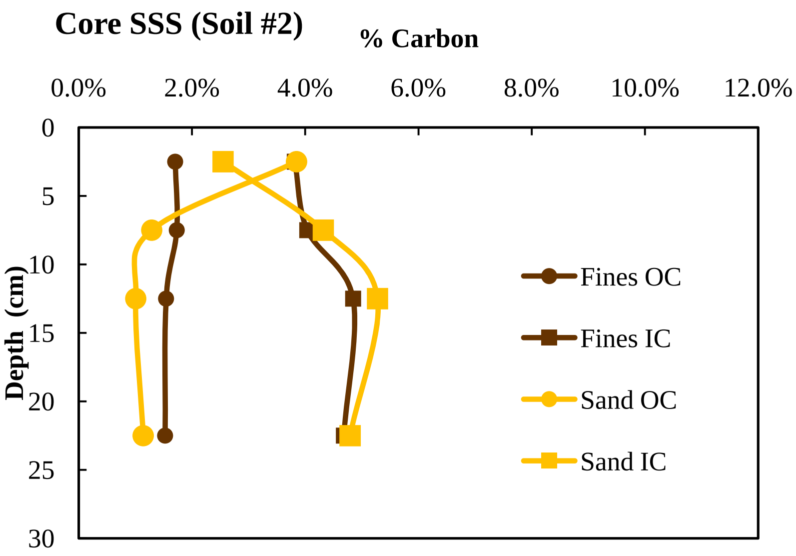


Choshui Watershed Loss on Ignition





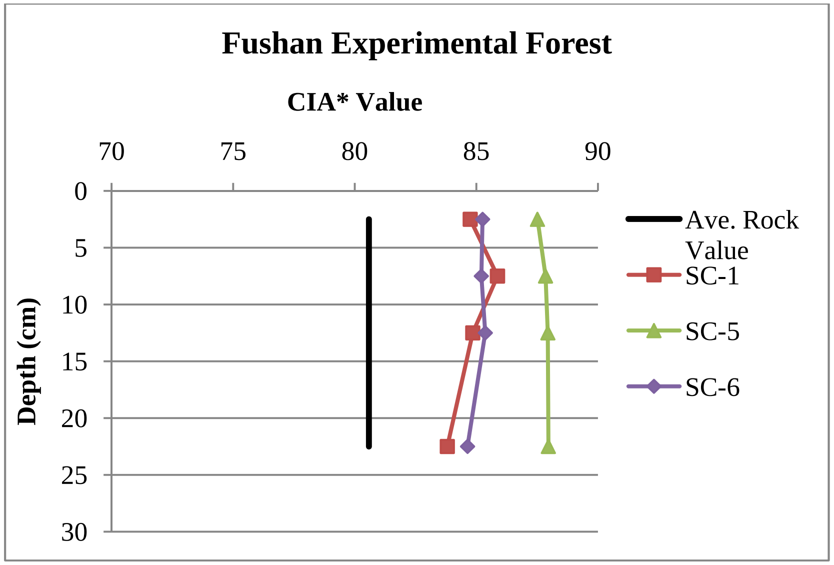
Core SSS (Soil #1)

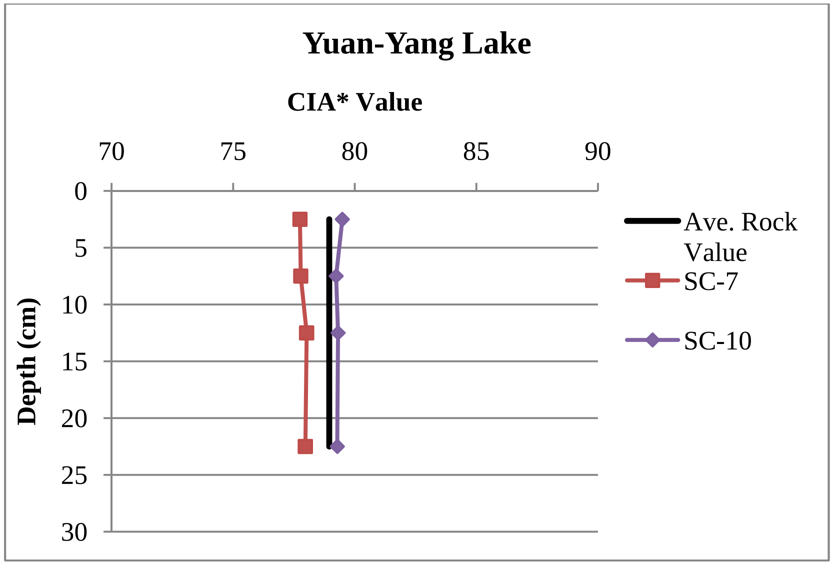


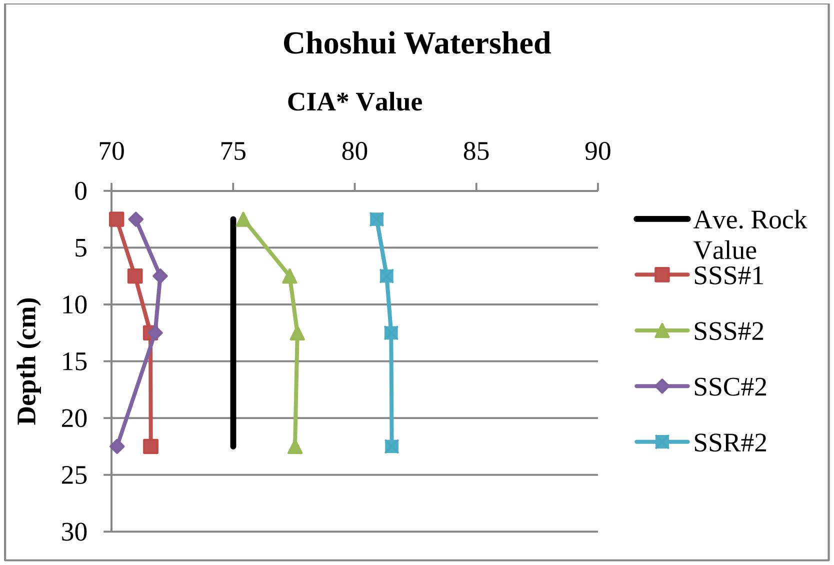
Core SSS (Soil #2)

Appendix C

CIA*


Fushan Experimental Forest


Yuan-Yang Lake


Choshui Watershed