Origin and chronosequence of paddy soils in China

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Abstract
The remains of nine ancient rice cultivation sites in the middle and lower reaches of Yangtze River were investigated. The remnants of 24 buried fields, each surrounded by ridges and irrigation ditches were discovered at 100cm depth at the Chuodun site in Kunshan County, China. Many fossil rice grains and utensils, such as pottery vessels and jars, were found in these fields. The fossil rice grains and soil organic matter were carbon dated and these fields were identified as the oldest irrigated rice paddy fields (6280 years BP) known today. It is suggested that the paddy soil developed at this site, at a depth of 100-200 cm was the first paddy soil in China. Based on our work a set of diagnostic criteria for distinguishing ancient paddy fields and soils was proposed. A chronosequence of paddy soils, 50-2000 years BP, developed from the same parent material, under the same ecological conditions and similar cropping systems was found in the south bank of Hangzhou Bay (30^0-30.5^0 N, 121^0-122^0 E). Preliminary results showed that soil fertility and accumulation of organic carbon in the top layer of these paddy soils gradually increased with the extent of cultivation.

Key Words
Ancient paddy soils, fossil rice grains, rice opal analysis, chronosequence, Yangtze river delta.

Introduction
Rice is the most important staple food for a large part of the world's human population. China has cultivated rice for more than 5000 years, but the location of the first irrigated paddy field and paddy soil is still being debated in scientific circles. Because of their longevity paddy fields are accepted as a form of sustainable land use, but historically it has been difficult prove that a field is an ancient paddy because of lack of direct evidence and systematic study. The purpose of this paper is to provide a set of criteria which will enable the ready distinction of relic sites and soils.

Methods
Soil scientists together with archeologists and local agricultural specialists conducted an investigation and excavation of 9 ancient rice cultivation sites in the middle and lower reaches of Yangtze River central China. The traditional methodology used by the Chinese archeologists (Ding 2004) for the excavation of relic sites was adapted for this study. The field survey, description of soil profiles, physical and chemical analyses were carried out according to the Standard Methods (Liu 1996), and the soils were classified according to Chinese Soil Taxonomy (Gong 1999).

Results
The remnants of 24 buried fields at the 100 cm depth layer in an open area of $300m^2$ at the Chuodun relic site ($31^0$24' N, $120^0$50' E), Kunshan County, Jiangsu Province, China were discovered. Each field is surrounded by ridges and irrigation ditches with water inlets and outlet (Figure 1; Cao *et al.* 2006). Based on the collected pottery, charred rice grains, with rice opal and pollen analysis as well as carbon dating these fields have been identified as the oldest (6280 years BP) irrigated rice fields known (Ding 2004, Cao *et al.* 2006) Accordingly the paddy soils developed here at the depth of 100-200cm (Figure 2) are believed to be the first lowland paddy soils in China. There are two buried ancient paddy soil profiles (3200 years BP and 6280 years BP) which overlapped in the main area (Figure 2, left) and described in Table 1. As the ancient settlers had very simple tools they could construct only very small paddy fields such as these (average area 6.85 m^2, range 0.4-16m^2), and had to bury human remains only 15 m from the main area (see skeleton upper right in Figure 1), where only one ancient (3200 years BP) paddy profile (Figure 2 right) had been observed.

Figure 1. Ancient paddy fields (1), ditches/ponds (2) and human skeleton (3) at the Chuodun relic site.

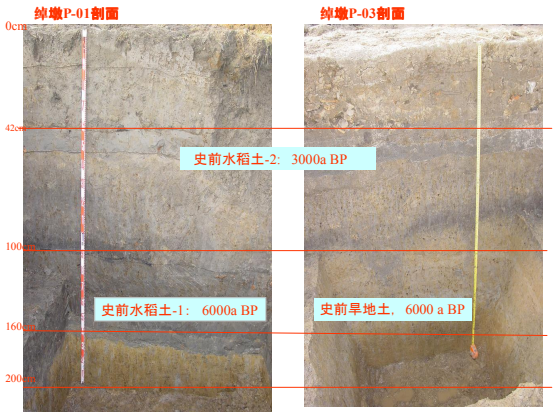

Figure 2. Two buried ancient paddy soils (L) and one buried ancient paddy soil (R) at the Chuodun relic site

Table 1 Morphological description of profile-01 at Chuodun relic site

Depth (cm)	Color	Structure	Texture	Fe & Mn mottles	Bio-remains	Rice opals (no./g)
00-15	10YR3/3	crumb	heavy loam	Many Fe mottles	many rice straw and roots	19476
15-22	10YR4/2	lumpy	heavy loam	Brownish mottles	some rice straw and roots	17093
22-42	10YR4/3	lumpy	light clay	Some Fe & Mn Conc.	a little straw and root	14147
42-57	10YR3/1	block	heavy loam	Silt film/many Fe&Mn Conc.	some Pottery pieces	25271
57-75	5YR4/1	non	light clay	Some Fe & Mn Concretion	a pottery piece	11477
75-100	5YR3/1	non	light clay	non		3542
100-116	10YR2/1	lumpy	heavy loam	Silt film/many Fe&Mn Conc	many charred grain	105159
116-130	10YR4/1	lumpy	heavy loam	Silt film/many	roots and leaves	64007
130-150	7.5YR4/1	lumpy	light clay	Fe mott. & Fe&Mn Conc	Hollow butt	17327
150-160	10YR5/1	block	light loam	Clayish Mott. & some Conc		19678
16-=174	10YR5/1	non	light clay	non		0
174-200	10YR4/6	block	light clay	non		0

As part of our studies, we developed a set of diagnostic criteria for distinguishing ancient paddy fields and soils (Cao 2008). These are; the fields/soils should (1) contain more than 50 fossil rice grains per m^2 of area or more than 5000 rice opals/g of soil; (2) be surrounded by bunds and ditches, and contain irrigation equipment and water sources for irrigation, (3) have clear boundaries with depletion or accumulation of clay, iron and other materials in the profile, (4) have specific pollen diagrams in the surface layer of the buried field and a specific magnetic susceptibility change in the profile, and (5) have specific ^{13}C NMR spectra of soil organic matter in the surface layer of the buried field. If the first and second criteria are met then the opened site can be considered as a buried ancient paddy field. Once a buried profile has met the third to the fifth criteria then it can be diagnosed as an irrigated paddy soil profile.

Although it is accepted that irrigated rice is a sustainable land use type, historically there is little direct evidence. A chronosequence of paddy soils was found in the south bank of Hangzhou Bay, located in Yuyao and Cixi counties (30^0-30.5^0 N, 121^0-122^0 E) of Zhejiang Province China. Between 1074 and 1993, 10-11 sea dikes were continuously constructed to create new farm land from coastal wetland. Consequently a chronosequence of paddy soils 50 to 2000 years old (Figure 3) was gradually formed. These paddy soils have developed from the same parent materials (coastal sediments), under the same ecological conditions and with the similar cropping systems (irrigated rice in summer and upland crops in winter). The fertility of the top soil layers of this chronosequence gradually increased with time of cultivation without the addition of chemical fertilizer (Figure 4 and Table 2).

The organic carbon concentration of the surface layer of these paddy soils gradually increased with time of cultivation to 700 years; since then there was little change (Table 2). The results suggest that organic carbon in the top layer of the paddy soils reached its ecological balance after 700 years. However, the dissolved organic carbon continually moving down and accumulated in the lower horizons (Table 3). The results show that paddy soil is an effective carbon pool even after it has been used for 700 to 2000 years.

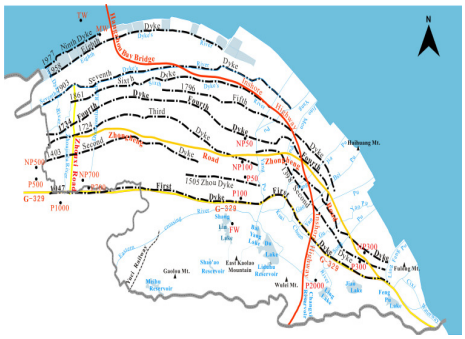

Figure 3. Coastal sediments and dikes on the layer South bank of Hangzhou Bay.

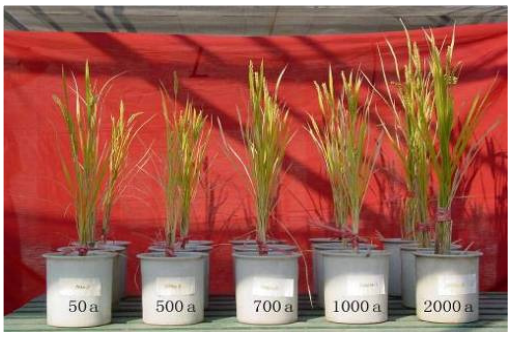

Figure 4. Natural soil fertility of the top of 50 to 2000 year old paddy soils.

Table 2. Soil fertility characteristics of the top layers of 50 to 2000 year old paddy soils.

Age (Years)	pH	TOC (g/kg)	Available P (mg/kg)	Available K
50	7.87	14.39	21.32	210.0
500	7.37	15.48	22.36	157.3
700	7.37	18.23	17.64	125.3
1000	6.93	19.95	26.67	234.7
2000	6.52	20.20	35.71	211.3

Table 3. Variation in organic carbon density in profiles of 50 to 2000 year old paddy soils.

Age (Years)	*D* 0-20cm (g/m^2)	*D* 0-40cm (g/m^2)	*D* 0-80cm (g/m^2)	*VR* (%)
50	3866.66	4785.30	6013.49	289.62
100	4402.01	5129.53	6525.86	267.36
500	2700.35	3380.74	4431.54	221.73
700	3438.21	4495.79	6131.30	174.89
1000	3432.49	4815.84	6904.87	130.53
2000	3502.08	5694.64	9333.90	56.48

Conclusions

1. A total of 24 buried fields of various sizes were located at 100cm depth in the Chuodun relic site, Kunshan, China and identified as the oldest (6280 years BP) irrigated paddy fields known. The results suggest that the paddy soil developed there at a depth of 100-200cm was the first paddy soil in China.
2. A set of diagnostic criteria for characterizing ancient paddy fields and ancient paddy soils was proposed.
3. A chronosequence of 50 to 2000 year old paddy soils developed from the same parent materials (coastal sediments), under similar ecological conditions and cropping systems were found in the south bank of Hangzhou Bay. Preliminary results showed that fertility and organic carbon accumulation in the top soil layer and the density of dissolved organic carbon in the lower layers of the soil profile gradually increased with time of cultivation,

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