water

MDPI

Article

# Organic Matter Clogging Results in Undeveloped Hardpan and Soil Mineral Leakage in the Rice Terraces in the Philippine Cordilleras

**Tomoyo Kurozumi [1], Yasushi Mori [1,*], Hiroaki Somura [1] and Milagros O-How [2]**

[1] Graduate School of Environmental and Life Science, Okayama University, Okayama 700-8530, Japan; pyri7j1p@s.okayama-u.ac.jp (T.K.); somura@okayama-u.ac.jp (H.S.)
[2] Universal Harvester Inc., 7th/8th Avenue, Cubao, Quezon City 1109, Philippines; moh_secretary@yahoo.com
* Correspondence: yasushim@cc.okayama-u.ac.jp

Received: 31 August 2020; Accepted: 9 November 2020; Published: 12 November 2020

check for updates

**Abstract:** Rice terraces in Cordillera, Philippines, a world cultural heritage site, are threatened by the risk of collapse. It is crucial to manage these rice terraces for their conservation, while simultaneously practicing traditional farming. We examined the soil environment and investigated its effects on rice terrace conservation, by focusing on the hardpan condition; infiltration process, which is related to the collapse of rice terraces; and soil nutrition conditions in these sites. Field survey and soil analysis revealed that in areas where the hardpan was not sufficiently developed and water infiltration was effectively suppressed, organic matter content was significantly high, suggesting organic matter clogging. In these rice terraces, the amounts of P, K, Ca, and Mn were significantly low, showing the mineral leaching under reductive soil conditions. Therefore, hardpan formation, rather than organic matter clogging, is essential for the suppression of infiltration and prevention of potential terrace collapse. Because hardpan formation or organic matter clogging cannot be identified from the surface of flooded rice paddies, it is difficult to identify the influencing factor. Thus, we suggest that the hard soil layer should be checked before the planting season and drainage is allowed after the cropping season in the rainy season.

**Keywords:** rice terrace; hardpan; infiltration; organic matter; clogging; Philippine Cordillera

## 1. Introduction

The Ifugao Rice Terraces in Luzon, Philippines, including the UNESCO World Heritage site "Rice Terraces of the Philippine Cordilleras", are the main agricultural production base of the area and considered a valuable asset for the traditional rice culture practiced in Ifugao. The terraces occupy 17,138 hectares of the total land area [1]. While the historic terraces cover an extensive area, the inscribed property consists of five clusters of the most intact terraces, which are the Nagacadan, Hungduan, Central Mayoyao, Bangaan, and Batad rice terraces [2].

In 2001, the Cordillera terraced rice fields were listed in the World Cultural Heritage in Danger, due to the deterioration of their physical integrity [3]. As this threat affects the social and economic aspects of life in this region, rural sociological measures, such as creating awareness, labor-intense activities, and funding, have been implemented to maintain rice terraces; consequently, the site was removed from the danger list in 2012 [4]. However, the threat has not been entirely addressed, because the crisis was resolved based on the sociological and cultural conditions surrounding the terraced rice fields, and not as a result of protection measures based on natural sciences. Rice terrace conservation activities have to be adapted to the field environment, such as water, soil, or nutrients.

In order to manage the rice terraces based on the scientific knowledge, several key issues should be addressed—that is, the cropping system in sloped fields with ridges to prevent soil erosion, effective water use management with limited water resources, and water holding hardpan at the bottom of the rice field.

Historically, potatoes were produced as the staple food in Ifugao. However, with improved irrigation and demand for higher yield and longer storage, the local communities developed their irrigation and farming system in the form of rice terraces [5]. Cropping in sloped field often suffer from the impact of heavy rainfall because heavy rainfall causes surface runoff which removes fertile surface soil. To prevent soil erosion during agricultural practices, ridges or levees were created, and fields were leveled to help retain water in the agricultural field. In this way, water that is supposed to flow down the slope is contained and used for crop cultivation, and it also prevents soil loss and helps maintain soil fertility in the fields. To efficiently use limited land, especially in countries with large mountainous areas, this technique, which is also culturally significant, is used as a means to conserve fertile soil environment [6]. There are two types of ridges: rice fields that have dykes formed by compacting the soil and rice fields where dykes are piled with stones. In some areas, both types of terraced rice fields can be seen together [7].

The terraces are often created in landslide areas because of abundant water supply and gentle slopes; consequently, these terraces can be easily cultivated using labor pool and water buffaloes or horses [7]. Farmers have used disasters, such as landslides, to their advantage by opening up their fields, building villages around the fields, and making a living from them. As paddy fields are built in natural environments, the use of water in the terraces plays an important role in preventing disasters by infiltrating/draining the water appropriately. The techniques of water use and management have been the local norms for sustainable agriculture in the region.

The drainage or infiltration of water from the field surface is a major factor for the increase in groundwater level in rice terraces. The surface water flow accounts for 92–98% of the total inflow in the area, whereas the amount of groundwater inflow/outflow is low [8]. Nanbu [9] reported that during irrigation and heavy rainfall, such as the typhoon period, the amount of infiltration in a paddy field is considerably higher than that in a forest area. During heavy rains, abandoned terraces have three times higher infiltration than cultivated terraces. When terraces are abandoned, macropores are created by soil animals, plants, and aggregation structures. The resulting soil structure has many pores, which result in higher hydraulic conductivity of both topsoil and subsoil (hardpan) [10,11]. These findings suggest that the conservation of the physical structure of rice terraces is crucial for controlling infiltration, and this infiltration is significantly related to the soil environment.

In general, rice terraces hold water by forming hardpans below the topsoil. Hardpans are created by heavy machinery/livestock/human traffic or repeated dry and wet process during the irrigation and dry season [12]. A well-formed hardpan can control infiltration and the groundwater level. If well designed, a hardpan can be formed within 3 years even if the fields are abandoned for a long time [13]. In addition, hardpan formation is important for maintaining soil nutrients and for holding water required for rice plant growth [14,15]. Another mechanism of infiltration control is the addition of clay soil as a subsoil [16,17]. The principle is different from that of hardpan formation by compaction; however, the fine particles of clay control infiltration by filling the pore gaps.

Here, we can recapture the background of the rice terraces from two aspects: (i) the geomechanical aspect, such as the formation of hardpan, dykes, and ridges to support the slopes and prevent slope failures, and (ii) effectively use limited water resources, such as by suppressing infiltration. These two aspects are strongly related to each other, and hardpan plays an important role in both. However, in Ifugao Province, rice paddies are always in a flooded condition. Therefore, the soil surface cannot be observed, or the soil profile cannot be thoroughly examined. Therefore, we focused on the formation and management of the hardpan, which would be a key factor for rice terrace conservation.

The objectives of this study were to examine the stability of hardpans and the development of infiltration suppression, and to assess the nutrient conditions in rice terraces, which influence the management of rice cultivation. We measured soil hardness, soil infiltration properties, soil particle distribution, organic matter (OM), and soil minerals. We conducted this study to understand the conservation techniques from a scientific perspective and help effectively manage rice terraces. This study is important for the conservation of terraced rice fields, the source of rice production in the region and a World Heritage site. It also addresses a common issue in Asia, where countries need to maintain rice paddies in an aging society. Therefore, the data of this study have widespread implications in the Asian monsoon zone.

## 2. Materials and Methods

### 2.1. Field Overview

We examined three rice terraces in Ifugao Province, namely Bangaan, Hapao, and Poblacion, which are shown in Figure 1. Bangaan and Hapao are located in Banaue and Hungduan Municipalities and are designated as UNESCO World Heritage sites. Poblacion in Banaue, which is declared a National Cultural Treasure by the Philippines Government, was also selected because of the restoration projects, which were ongoing during the study period.

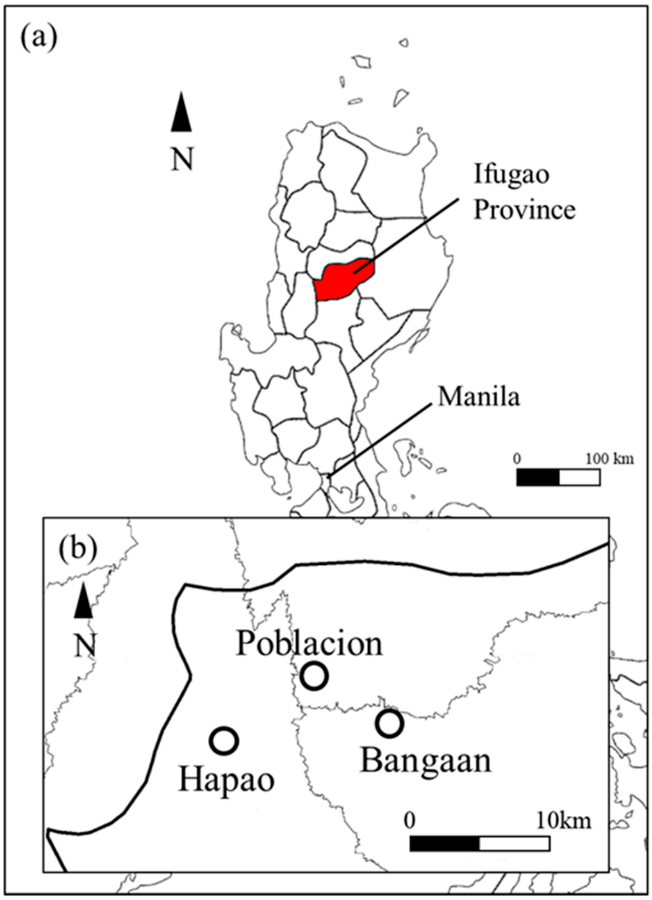


**Figure 1.** Site map for (**a**) Ifugao province and (**b**) sampling villages.

Bangaan has terraced rice fields on a steep natural slope (20°) heading toward the valley, with schools upstream and a village in the middle. Poblacion has many reconstructed rice terraces, and it is positioned as a landmark for rice terrace restoration projects. There are rice terraces at an average inclination of 45°; many levees are not well maintained in Poblacion. In Hapao, almost all levees are fixed with concrete and the slope is gentle; therefore, movement between rice terraces was the easiest among the three sites.

All rice paddies in these sites are maintained in a flooded condition to avoid crack or fissure that results in collapse [18]. Therefore, the soil surface cannot be observed, or the soil profile characteristics cannot be thoroughly examined.

*2.2. Field Research and Sampling*

We first visited the fields in April 2017 to obtain permission to survey the World Heritage site, and then in August 2017 to interview the local people and select sampling sites. We conducted field surveys in Bangaan, Hapao, and Poblacion in March 2018. We collected soil samples at depths of 0, 10, and 30 cm, from each rice paddy, at three different elevations, namely, upper, middle, and lower elevation, based on the relative elevation of each site (Figure 2).

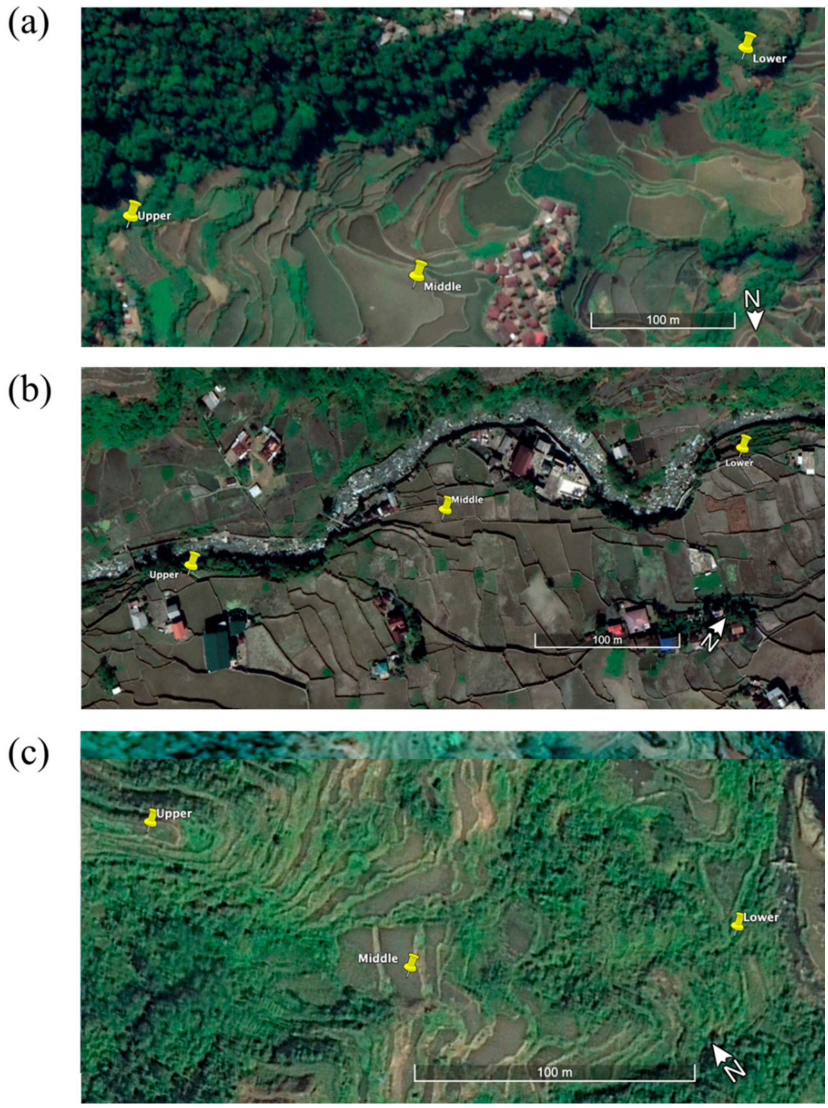


**Figure 2.** Sampling location (**a**) Bangaan, (**b**) Hapao, and (**c**) Poblacion (cited from Google Earth Pro ver. 7.3.3.7669).

As rice fields are always flooded, soil sampling was conducted using a 1-mm thick aluminum cylinder container (50 mL) with a small hole for water and air to escape during sampling. The cylinder was gently pushed into the mud and pulled out; then the soil sample was transferred to a plastic container for storage.

Soil hardness was tested using a digital cone penetrometer (DIK-5532; Daiki Rika Kogyo Co., Ltd., Saitama, Japan). The vertical profiles of soil hardness were obtained by inserting the cone (2 $cm^2$) into the rice paddy field to a depth of 60 cm; the measurement was performed at three points in each paddy field. The infiltration rate was measured in triplicate using the Rapid Leakage Capacity Tester (DIK-4350; Daiki Rika Kogyo Co., Ltd., Saitama, Japan). The leakage test device consisted of a 14 cm wide × 14 cm deep cylinder connected to a 3.5-mm diameter plastic pipe gauge at the top to measure infiltration. The cylinder was set in a rice paddy field, and the cylinder and plastic pipe were filled with water. Subsequently, vertical infiltration was measured by recording the water level on the plastic pipe gauge. The device should be saturated with water without air to maintain hydraulic continuity.

### *2.3. Laboratory Experiment and Analysis*

All soil samples were weighed to determine water content and bulk density, and oven dried at 80 °C to avoid OM decomposition. They were then ground and sieved through a 2-mm mesh for further analysis.

Total carbon and nitrogen concentrations in soil samples at the 0, 10, and 30 cm depths were measured using an Elemental Analyzer (2400 Series II CHNS/O; Perkin Elmer, Inc., Waltham, MA, USA). Exchangeable cations were measured using an inductively coupled plasma (ICP) multi-type atomic emission spectrometer (ICPE-9820; Shimadzu Corporation, Kyoto, Japan). Briefly, ammonium acetate solution (pH 7) was added to 1 g of the soil sample, and the mixture was stirred for 1 h, filtered (0.45 μm filter), and diluted (10 times) for ICP measurement. Since the purpose of the study was to examine and compare the soil environment affected by the management practices, and not to measure the nutrient status for plant growth, ammonium acetate extraction for exchangeable cations was employed for all samples.

Particle size distribution analysis was performed using the Laser Diffraction Particle Size Analyzer (SALD-3100; Shimadzu Corporation, Kyoto, Japan). To approximately 70 mg of soil from each sample, 5% hydrogen peroxide solution was added for organic matter decomposition. Thereafter, sodium hexametaphosphate was added as a dispersant. Particle size distribution was analyzed by circulating 40–200 mg of soil in a water bath, irradiating with a laser source, and analyzing the resulting diffraction patterns.

Soil water electrical conductivity (EC) was measured using the 1:5 (soil:water) extraction method with a conductivity meter (B-771 LAQUA twin; Horiba Ltd., Kyoto, Japan). The soil pH was measured using the 1:2.5 (soil:water) extraction method with a compact pH meter (LAQUA twin B-71X; Horiba Ltd., Kyoto, Japan). Statistical analysis was performed using SPSS Statistics software (IBM, Chicago, IL, USA).

## 3. Results and Discussions

The basic properties of the soil samples are shown in Table 1. The bulk density of soil was low, because all fields were in flooded conditions. Most soil textures were of the loam type, with a few silty loam types in Bangaan and Poblacion, and also sandy loam type in Hapao. The EC was not significantly different among the samples. With a decrease in elevation, the soil pH showed a slightly decreasing trend in both Bangaan and Poblacion, but a slightly increasing trend in Hapao.

**Table 1.** Basic properties of soil samples from rice terraces in Bangaan, Hapao, and Poblacion.

| | | Depth | Dry Bulk Density | Particle Distribution Clay | Silt | Sand | EC | pH | Total Carbon | Total Nitrogen |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (cm) | (g/cm$^3$) | (%) | | | (mS/cm) | | (%) | (%) |
| Bangaan | Upper | 0 | 0.44 | 15.62 | 50.70 | 33.68 | 0.15 | 7.1 | 2.42 | 0.23 |
| | | 10 | 0.46 | 12.24 | 40.28 | 47.48 | 0.13 | 6.2 | 2.52 | 0.21 |
| | | 30 | 0.80 | 16.49 | 49.77 | 33.74 | 0.09 | 6.5 | 1.73 | 0.16 |
| | Middle | 0 | 0.26 | 14.08 | 43.32 | 42.60 | 0.12 | 6.3 | 3.32 | 0.28 |
| | | 10 | 0.52 | 17.96 | 46.98 | 35.07 | 0.11 | 6.0 | 2.40 | 0.22 |
| | | 30 | 0.78 | 18.01 | 49.07 | 32.92 | 0.11 | 6.0 | 1.93 | 0.19 |
| | Lower | 0 | 0.56 | 11.03 | 43.02 | 45.96 | 0.13 | 6.2 | 2.04 | 0.18 |
| | | 10 | 0.72 | 12.00 | 45.00 | 43.00 | 0.12 | 5.6 | 1.77 | 0.16 |
| | | 30 | 0.73 | 11.79 | 40.14 | 48.07 | 0.09 | 5.8 | 2.10 | 0.18 |
| Hapao | Upper | 0 | 0.22 | 19.86 | 47.33 | 32.81 | 0.13 | 5.9 | 5.28 | 0.44 |
| | | 10 | 0.27 | 20.17 | 45.57 | 34.26 | 0.12 | 5.8 | 5.11 | 0.40 |
| | | 30 | 0.35 | 19.98 | 45.90 | 34.12 | 0.09 | 5.6 | 4.70 | 0.33 |
| | Middle | 0 | 0.33 | 10.25 | 37.58 | 52.18 | 0.10 | 6.0 | 3.52 | 0.28 |
| | | 10 | 0.39 | 10.36 | 41.97 | 47.67 | 0.08 | 5.8 | 3.55 | 0.26 |
| | | 30 | 0.44 | 17.69 | 37.10 | 45.21 | 0.08 | 5.8 | 3.23 | 0.25 |
| | Lower | 0 | 0.50 | 11.66 | 27.63 | 60.71 | 0.14 | 5.8 | 5.13 | 0.40 |
| | | 10 | 0.63 | 13.22 | 43.68 | 43.11 | 0.19 | 7.7 | 3.60 | 0.29 |
| | | 30 | 0.38 | 26.15 | 39.53 | 34.32 | 0.09 | 6.1 | 5.42 | 0.49 |
| Poblacion | Upper | 0 | 0.57 | 20.42 | 49.37 | 30.21 | 0.13 | 7.0 | 2.30 | 0.20 |
| | | 10 | 1.08 | 14.30 | 40.30 | 45.40 | 0.05 | 7.2 | 0.84 | 0.08 |
| | | 30 | 1.12 | 17.61 | 51.69 | 30.71 | 0.05 | 7.1 | 1.45 | 0.13 |
| | Middle | 0 | 0.42 | 17.43 | 51.15 | 31.42 | 0.16 | 6.7 | 2.97 | 0.26 |
| | | 10 | 0.37 | 16.81 | 54.22 | 28.97 | 0.12 | 6.4 | 3.15 | 0.27 |
| | | 30 | 0.72 | 13.80 | 44.27 | 41.94 | 0.11 | 6.1 | 2.09 | 0.17 |
| | Lower | 0 | 0.41 | 13.90 | 46.36 | 39.74 | 0.22 | 6.6 | 3.59 | 0.28 |
| | | 10 | 0.40 | 15.63 | 49.82 | 34.55 | 0.25 | 6.5 | 3.35 | 0.26 |
| | | 30 | 0.52 | 17.14 | 40.10 | 42.76 | 0.26 | 6.3 | 3.04 | 0.24 |

### *3.1. Hardpan Formation*

The soil hardness profiles are shown in Figure 3. In most of the locations and the elevations, soil hardness increased gradually from 10 to 20 cm, with some peaks at 20–50 cm; the troughs and crests in the figure show these variations in the hardpan. The peaks varied from one site to another. In some fields, the peaks were not apparent. Generally, the plough layer, where rice seeds are usually planted, is 0–20 cm deep, and thus a hardness peak at a depth of 40 or 50 cm would be rather deep.

Soil hardness of approximately 1000 kPa or more can restrain water infiltration in a highly water-retaining Andosol [19]. Similar values, 813–911 kPa, were reported for gley upland soils [20]. Thus, we used 1000 kPa as a standard to determine the presence or absence of a hardpan layer. Presence of hardpan was confirmed when a continuous hardness of more than 1000 kPa was observed for more than 3 cm of the soil profile. The results of the soil hardness tests showed that the nine rice terraces (upper, middle, and lower sections in Bangaan, Hapao, and Poblacion) surveyed can be divided into two groups. Five sites fulfilled the standard hardness criterion, with a layer of more than 1000 kPa hardness, whereas in the other four sites, the soil hardness did not fulfill the standard hardness criterion (Table 2).

Among the reasons for lack of hardpan could be the inability to maintain the field by plowing with heavy machinery or water buffaloes. Only a few farmers have access to water buffaloes for plowing the soil, and thus, the compaction of the subsoil layer is insufficient; moreover, heavy machineries, such as tractors, are not allowed for plowing. Another reason is the rice terraces are always flooded. A factor that favors hardpan layers is the repeated dry and wet process during the irrigation and dry season [12]. Insufficient soil compaction can be attributed to the decrease in interparticle binding force. Moreover, constant flooding prevents the cohesion of soil particles at the bottom.

In Hapao, all three fields lacked hardpans, possibly because of the concrete dykes; hence, the farmers were less concerned about the physical maintenance of their fields, including the formation of hardpans.

**Table 2.** Statistical classification of the sampling site by hardpan formation.

| Group | Sampling Point | | Samples n |
|---|---|---|---|
| With hardpan (>1000 kPa) | Bangaan | Upper<br>Lower | 12 |
| | Poblacion | Upper<br>Lower | |
| Without hardpan (<1000 kPa) | Bangaan | Middle | 15 |
| | Hapao | Upper<br>Middle<br>Lower | |
| | Poblacion | Middle | |

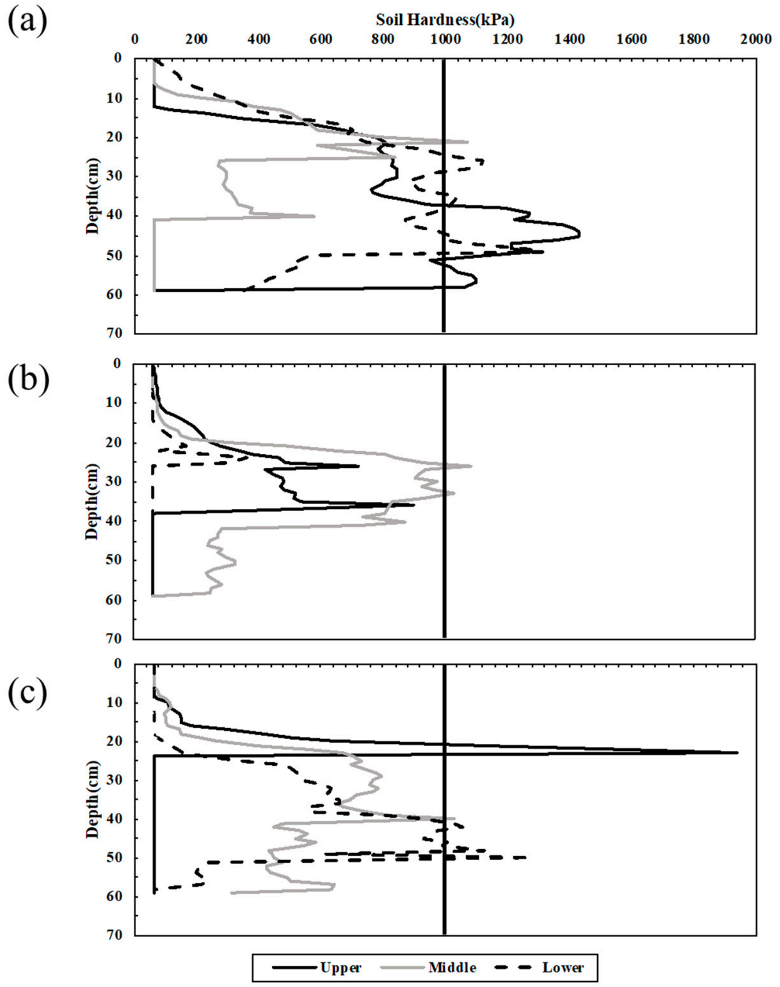


**Figure 3.** Soil hardness profile (kPa) (**a**) Bangaan, (**b**) Hapao, and (**c**) Poblacion.

*3.2. Infiltration Rate Control*

The infiltration rate in the three sites is shown in Figure 4. In general, a standard infiltration rate is 15 mm/day [21] with the upper limit of approximately 25 mm/day for high yield [22]. As established, infiltration can be substantially low when a hardpan is successfully formed. However, the results showed that infiltration rate in these areas was within or below the range, regardless of the formation of hardpans, with no significant difference between the two groups in terms of soil hardness profile.

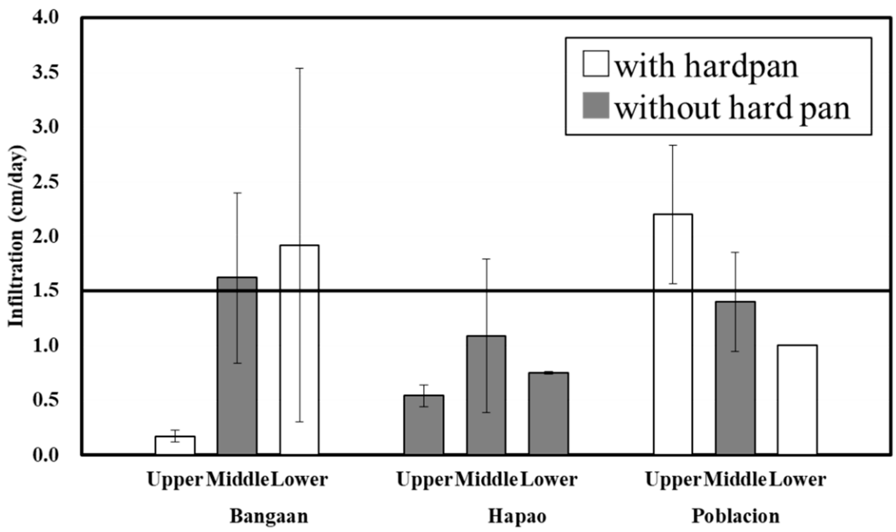


**Figure 4.** Infiltration rate (cm/day) for Bangaan, Hapao, and Poblacion. Measurement was conducted only once in the lower fields of Poblacion owing to gas emission.

It should be noted that gas bubbles from the soil often intruded the infiltration tube during measurements. Considering the anaerobic flooded conditions and the presence of bubbles in situ, we hypothesized that the gas emitted was methane, $CH_4$. Carbon dioxide and hydrogen were ruled out because the former dissolves in water and is not expected to be present in anaerobic conditions, and the latter is usually utilized in the production of methane gas [23]. If our hypothesis is correct, methane gas emission can obstruct the sedimentation of soil particles, which can lead to undeveloped hardpan.

*3.3. Effect of Organic Matter*

The results of soil hardness profiles and infiltration rate suggest that infiltration is controlled by factors other than hardpan formation. Infiltration suppression can be achieved by not only creating a dense layer by compaction but also clogging. Clogging might occur by fine clay minerals, which can swell.

We examined the clay content in each soil sample in relation to infiltration without hardpan formation. However, there was no significant relationship (Mann–Whitney U test, 5%); this indicated that the content of fine particles was not related to appropriate infiltration without hardpan formation.

We also examined the total carbon (TC) as an indicator of OM, for infiltration suppression without hardpan formation (Figure 5). Highly viscous and sticky properties of OM can control infiltration. The results of the Mann–Whitney U test (5%) showed that there was a significant difference in the TC concentration. Thus, in rice terraces, a relatively higher OM content can control infiltration by clogging, without the formation of hardpan.

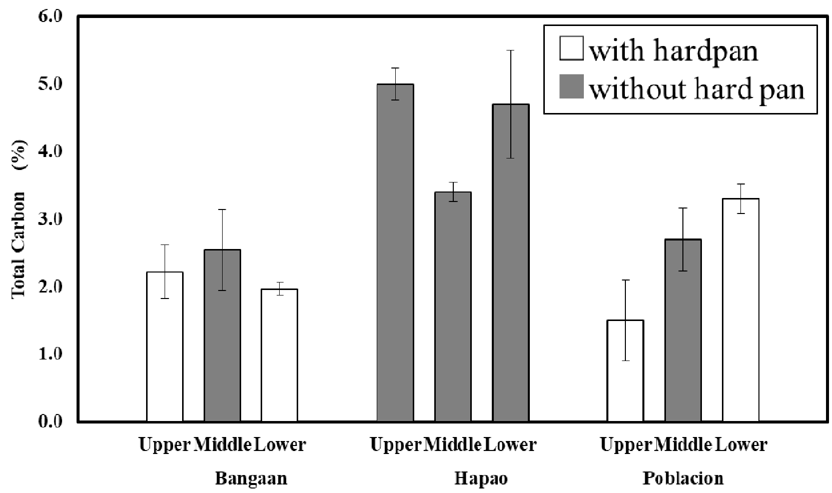


**Figure 5.** Total carbon content (%) for Bangaan, Hapao, and Poblacion.

Touch [24] reported that organic mud in the soil could greatly reduce hydraulic conductivity. Zhao [25] used wastewater as an OM source and showed that OM is a major factor influencing biofilm growth, which accelerates the decrease in infiltration rate. Furthermore, microbial activity causes clogging, and thus, gradually decreases soil-infiltration ability in the long term [26,27].

In the rice terraces in the Cordilleras, infiltration control is appropriately performed and flooding is maintained. However, there are rice terraces with undeveloped hardpans; this indicates a high OM content in these areas. That is, in areas where hardpans are poorly formed, it is highly possible that infiltration control occurs by the clogging of OM. Gas bubble intrusion in the tube during the infiltration test further supports this result.

### *3.4. Characteristics of Minerals in Rice Terraces under Constantly Flooded Conditions*

The soil chemical environment affected by hardpan formation was examined in the present study. In addition to total C and N measurement, Ca, K, Mg, Mn, and P were effectively extracted from the soils and measured by ICP. First, major nutrients, N, P, and K are shown in Figure 6. There were significant differences in the concentration of nutrients between the groups with and without hardpans (Mann–Whitney U test, 5%). When hardpans were not sufficiently developed, N was significantly high, which was the same trend for total C in Figure 5. C/N correlation supported the estimation that organic matter clogging suppresses infiltration. On the other hand, P and K were significantly low when hardpans were not sufficiently developed. Similarly, in Figure 7, Ca, K, and Mn showed significantly low concentrations (Mann–Whitney U test, 5%) when hardpans were not sufficiently developed. The pH also showed a similar trend (Figure 7): it was higher in areas with hardpan and contrary in areas without hardpan (Mann–Whitney U test, 5%).

A potential reason for mineral leakage would be pH and reductive soil condition. Although there was a significant difference in pH with or without hardpan, the range of pH was appropriate for agricultural practices for major crops [28]. Thus, we hypothesized that mineral leakage was caused by the development of reductive conditions. Gas emission or mineral leakage was usually determined by Oxidation-Reduction Potential (ORP). Based on methane gas emission (ORP below −150 mV; [29]), reductive conditions were sufficient for Mn leakage (ORP below the range of +200 to +400 mV; [30]), and P would be released from the soil particles along with Ca [31].

K is usually not associated with pH or reductive conditions, but it is easily leached by ion exchange. Undeveloped hardpans indicated that soft soil layers could be deep; therefore, in this case, K would move to a deeper profile with water movement. This soft layer will also help to transport other minerals, such as Mn, Ca, and P to deeper profiles.

The above process of ion leaching into the deeper profiles is estimated, as ionization progressed under the reductive anaerobic conditions with abundant OM [32]. Fields with undeveloped hardpans and higher OM content allowed ionized minerals to move deeper down the soil profile.

These experimental results were supported by the conditions of rice terraces, which are flooded throughout the year to avoid crack development under dry conditions and the subsequent collapse. In addition, the sewage system is not systematic, and we experienced the malodor of wastewater in several rice terrace sites.

### *3.5. Effective Management for Rice Terraces in Ifugao Province*

Infiltration can be controlled via hardpan formation by compaction and clogging by OM. However, both hardpan formation and OM clogging cannot be identified from the surface of flooded rice paddies. Therefore, it is difficult to identify the influencing factors. Although flooded conditions are crucial for rice terrace management, OM clogging may cause nutrient leaching and greenhouse gas emission, creating strong reductive conditions. Moreover, undeveloped hardpans cause deeper saturated profiles, with a heavy soil layer inside the dyke. This condition could eventually lead to the potential risk of ridge collapse.

Therefore, we suggest that the local people or government should check the depth of the hard soil layer before the planting season in rice terraces. The hard soil layer is confirmed by inserting a stick-like tool into the soil. If this is not sufficient, a compaction process might be needed. We also suggest appropriate drainage in rice terraces. Among the reasons for this is to decompose the easily degradable OM to avoid strong reductive conditions. The drainage should be preferably conducted after the cropping season—that is, September or October—which is still in the rainy season. Thus, the rainfall would flood the rice terraces in a relatively short period. Another reason is to develop hardpans. Hardpans can be formed by heavy machine/animal traffic. Besides these, the repeated dry and wet process allows soil particles to sediment and stick to each other, creating a stable cultivar base. Although it is necessary to carefully monitor soil moisture conditions in order to avoid crack development, drainage is a simple option to maintain rice terraces.

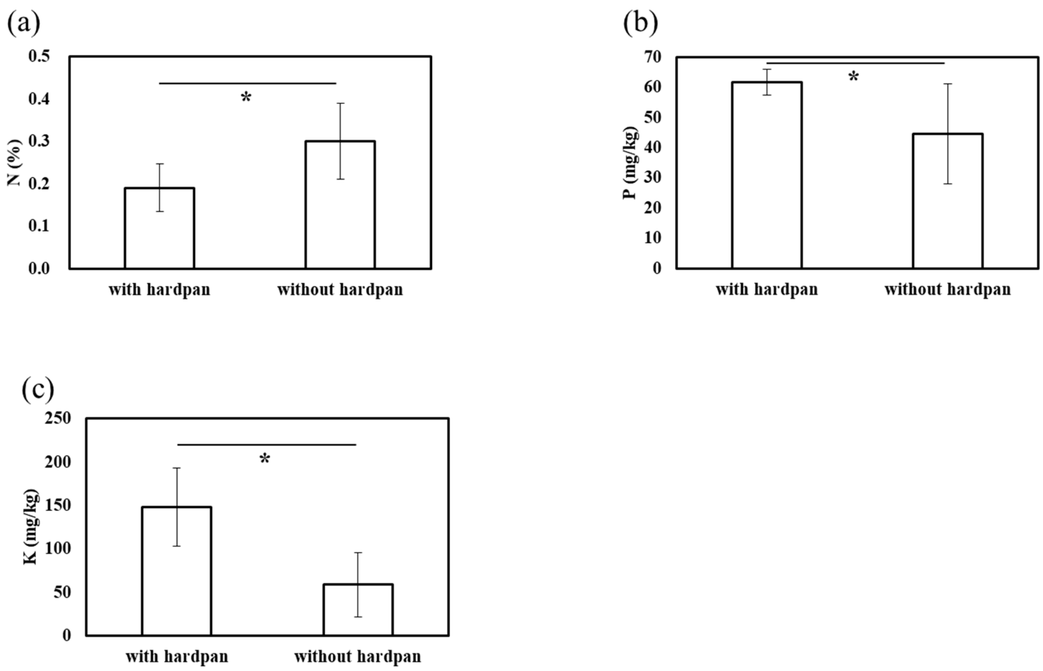


**Figure 6.** Mineral contents in two groups categorized by hardpan formation. (**a**) Total nitrogen, (**b**) phosphorus, and (**c**) potassium. (*: Mann–Whitney U test, $p < 0.05$).

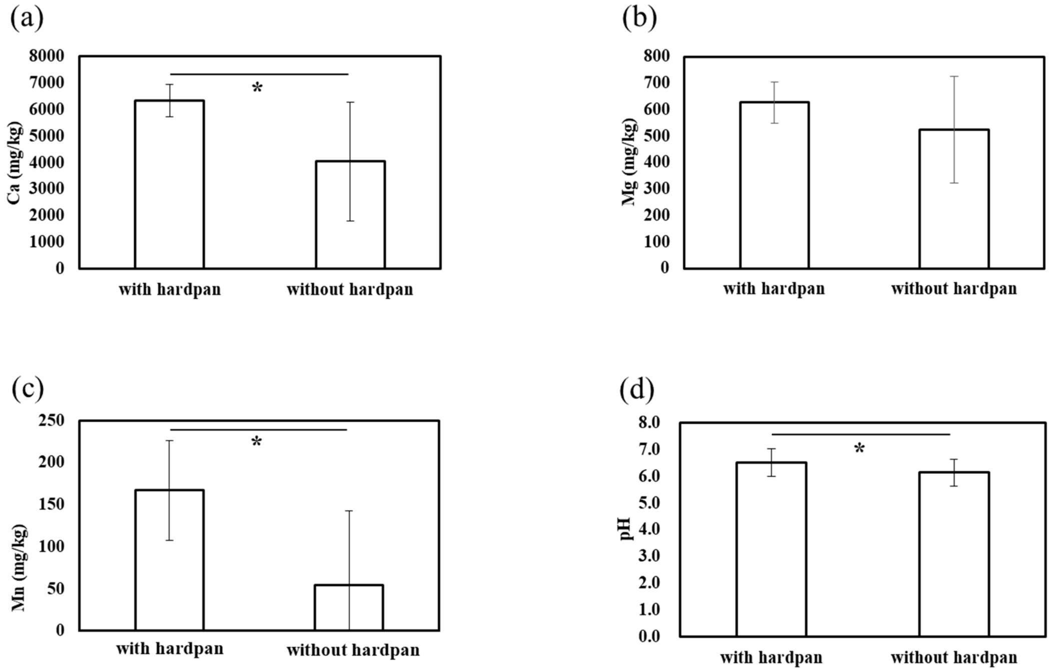


**Figure 7.** Mineral contents and pH in two groups categorized by hardpan formation. (**a**) Calcium, (**b**) magnesium, (**c**) manganese, and (**d**) pH. (*: Mann–Whitney U test, $p < 0.05$).

## 4. Conclusions

With the ultimate aim of contributing to the conservation of rice terraces in the Cordilleras, soil environmental factors were examined. As the site is always flooded, soil hardness and infiltration rate were measured in situ, whereas the sampled soils were analyzed in the laboratory. The following results were obtained:

1. The infiltration rate was fairly controlled regardless of the formation of hardpans. If hardpans were not sufficiently developed, the sites had significantly higher OM content. The infiltration rate was considered to be controlled by clogging the OM, which was supported by the frequent gas emission in the infiltration test.
2. The concentration of exchangeable cations was significantly lower when hardpans were not sufficiently developed. Continuous flooding and higher OM content resulted in reductive conditions, leading to ionization or mobilization in the reductive deep saturated vertical profile.
3. These factors cannot be recognized as long as the flood is effectively maintained in the rice terraces. However, the local people or government should check the depth of the hard soil layer before the planting season for better management of rice terraces.

**Author Contributions:** Conceptualization, Y.M.; methodology, T.K.; formal analysis, T.K.; investigation, T.K., H.S., and Y.M.; resources, M.O.-H.; writing—original draft preparation, T.K.; writing—review, editing, and supervision, Y.M.; funding acquisition, Y.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was partially supported by The Japan Society for the Promotion of Science, NEXT program (GS021, 2011–2014), KAKENHI(B) (26292127, 2014–2016), KAKENHI(B) (17H04484, 2017–2019), and KAKENHI(A) (17H01496, 2017–2020).

**Acknowledgments:** We are grateful to the local government, organizers, and people in Banaue and Hunduan regions who permitted us to conduct this research. The authors are also grateful to Ken'ichiro Hidaka for his valuable comments for this research and to Megumi Kosaka and Motonari Kobayashi at Division of Instrumental Analysis for the measurements of C/N analyses.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Marlon, M. The rice terraces of Ifugao Province, Philippines. *J. World Herit. Study* **2017**, 1–5. [CrossRef]
2. ICOMOS; IUCN. *World Heritage List Rice terraces of the Cordilleras No.722*; Advisory Body Evaluation (ICOMOS); UNESCO: London, UK, 1995; pp. 48–52.
3. UNESCO. *Justification for Inscription on the List of World Heritage in Danger*; Report of the 25th Session of the Committee; UNESCO: London, UK, 2001; pp. 1–157.
4. UNESCO. *Establishment of the World Heritage List in Danger (Removed Properties)*; Decision 36 COM 8C.3; UNESCO: London, UK, 2012; p. 222.
5. Acabado, B.S. Taro before rice terraces: Implications of radiocarbon determinations, ethnohistoric reconstructions, and ethnography in dating the Ifugao Terraces. *Senri Ethnol. Stud.* **2012**, *78*, 285–305.
6. Nakajima, M. Multi-faceted function of rice terraces and conservation efforts. *Water Resour. Environ.* **2000**, *13*, 35–41.
7. Rice Terrace Research Association. *Introduction of Rice Terraces*; Keisou shobo: Tokyo, Japan, 2014; pp. 23–45.
8. Onishi, T.; Horino, H.; Mitsuno, T. Evaluation of groundwater properties in terraced paddy fields using transient unsaturated-saturated water flow analysis. *Trans. Jpn. Soc. Irrig. Drain. Rural Eng.* **2003**, *227*, 97–104.
9. Nanbu, T. Study on Water Cycle Mechanism of Terraced Paddy Field and Landslide Area in Mountainous Area. Ph.D. Thesis, Okayama University, Okayama, Japan, 2014.
10. Chiba, K.; Baba, H. Soil physical properties of uncultivated paddy fields located in semi-wet sloping land and the simulation of their response to heavy rain. *Trans. Jpn. Soc. Irrig. Drain. Rural Eng.* **1997**, *190*, 61–70.
11. Iwata, F.; Narioka, H. Change of soil structure and plant succession of renounced in hilled rural area. *J. Jpn. Soc. Irrig. Drain. Rural Eng.* **2002**, *70*, 207–210.
12. Nakatsuka, K.; Ishii, K. Hardpan formation and rice root distribution (in Japanese). *J. Agric. Sci.* **1989**, *44*, 392–396.
13. Mori, Y.; Sasaki, M.; Morioka, E.; Tsujimoto, K. When do rice terraces become rice terraces? *Paddy Water Environ.* **2019**, *17*, 323–330. [CrossRef]
14. Mather, T. *FAO Irrigation and Drainage Environmental Management for Vector Control in Rice Fields*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1984; p. 39.
15. Podder, M.; Akter, M.; Roy, S. Impacts of plough pan on physical and chemical properties of soil. *J. Environ. Sci. Nat. Resour.* **2012**, *5*, 289–294. [CrossRef]
16. Chapuis, R. Sand-bentonite liners: Predicting permeability from laboratory tests. *Can. Geotech. J.* **1990**, *27*, 47–57. [CrossRef]
17. Naito, E.; Baba, M. Study on the decrease of percolation water in paddy fields by using bentonite (III). *Agric. Eng. Res.* **1955**, *23*, 161–163.
18. Mori, Y.; (Graduate school of Environmental and Life Science, Okayama University, Okayama, Japan). Personal Communication, 2017.
19. Kanmuri, H.; Chiba, K. Reducing dry Andisol paddy field permeability of direct-seeding rice cultivation using plowing and compaction. *J. Irrig. Drain. Rural Environ.* **2012**, *282*, 69–77.
20. Ota, T.; Taniyama, I.; Kusaba, T.; Araya, H. Changes in the soil properties of terrace paddy. *Soil Phys. Plant Growth Jpn.* **1996**, *73*, 3–10.
21. Shiozawa, S.; Yamaji, E.; Yoshida, S. *Environmental Agricultural Land Engineering*, 2nd ed.; Buneido syuppan: Tokyo, Japan, 2016; p. 38.
22. Anase, M.; Koide, S.; Takenaka, H. *Agricultural Land Engineering*; Buneido Syuppan: Tokyo, Japan, 1983; p. 29.
23. Tokida, T.; Mizoguchi, M. Ebullition of methane from peat with falling atmospheric pressure. *Geophys. Res. Lett.* **2005**, *32*, L13823. [CrossRef]
24. Touch, N.; Hibino, T. Model of permeability reduction due to mud deposition in the pores of sand beds. *J. Jpn. Soc. Civ. Eng. Ser. B1 Hydraul. Eng.* **2012**, *6*, 547–552.
25. Zhao, L.; Tong, W. Clogging processes caused by biofilm growth and organic particle accumulation in lab-scale vertical flow constructed wetlands. *J. Environ. Sci.* **2009**, *21*, 750–757. [CrossRef]
26. Mori, Y.; Suetsugu, A.; Matsumoto, Y.; Suyama, K. Enhancing bioremediation of oil-contaminated soils by controlling nutrient dispersion using dual characteristics of soil pore structure. *Ecol. Eng.* **2013**, *51*, 237–243. [CrossRef]

27. Mori, Y.; Fujihara, A.; Yamagishi, K. Installing artificial macropores in degraded soils to enhance vertical infiltration and increase soil carbon content. *Prog. Earth Planet. Sci.* **2014**, *1*, 30. [CrossRef]
28. Doran, J.; Jones, A. *Methods for Assessing Soil Quality*; Soil Science Society of America, Inc.: Madison, WI, USA, 1996; Volume 49, p. 173.
29. Pun, I.; Yamaji, E. Methane emission trend based on the water management during rice growing and non-growing seasons. *J. Rice Res.* **2016**, *4*, 176. [CrossRef]
30. Aoyama, I. Behavior of iron and manganese in an aquatic environment. *Soil Phys. Cond. Plant Growth* **1993**, *57*, 11–18.
31. Kamiya, H.; Ohshiro, H.; Tabayashi, Y.; Kano, Y.; Mishima, K.; Godo, T.; Yamamuro, M.; Mitamura, O.; Ishitobi, Y. Phosphorus release and sedimentation in three contiguous shallow brackish lakes, as estimated from changes in phosphorus stock and loading from catchment. *Landsc. Ecol. Eng.* **2011**, *7*, 53–64. [CrossRef]
32. Hurt, G. Hydric soils. In *Encyclopedia of Soils in the Environment*; Elsevier: Amsterdam, The Netherlands, 2005; pp. 212–217.