Evaluation of Soil Hardness in Paddy Fields by Cone Penetrometer as a Simple Soil Physical Diagnosis Method

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Abstract
To enable quantitative soil physical diagnosis by cone penetrometer, this study investigated time-course changes in the three-dimensional (3D) distribution of soil hardness and quantified the effect of land leveling on soil compaction. The most important result is that the 3D distribution of soil hardness in the field can be mapped quickly. One person could survey 1 ha to 60 cm depth in 90 min. The method allows several fields to be screened in a short time. The results of cluster analyses based on the horizontal distribution of soil hardness show that the distribution did not change significantly throughout the year. Although absolute values can change, this method can be used to measure soil hardness at any time of the year. Measurement of soil hardness by depth can detect the range or position of the plow pan. Comparison of the distribution of soil physical properties between fields revealed that field management affects hardness, especially in the plow layer and plow pan.

Keywords
cone penetrometer, paddy field, soil hardness, 3D distribution, Yamanaka hardness index, soil physical diagnosis

Introduction
In Japan, in response to decreases in the price of rice and in rice consumption, paddy fields have been converted to upland fields to grow maize, wheat, and vegetables (MAFF 2016a). In consequence, the importance of soil physical diagnosis has increased (Anzai 2016). Japanese agriculture continues to contract as farmers age and the working population decreases (MAFF 2016a, MAFF 2017). In response, work efficiencies have been improved through increases in the scale of management (Shimizu 2017), such as field consolidation and the use of larger machinery (MAFF 2016a, MAFF 2017). In response, work efficiencies have been improved through increases in the scale of management (Shimizu 2017), such as field consolidation and the use of larger machinery (MAFF 2016a, MAFF 2017). This move toward extensive agriculture requires simple and quick techniques for soil physical diagnosis of large areas in less time.

In addition, according to the Fifth Assessment Report of the IPCC (2013), extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century as the global mean surface temperature increases. In Japan, extreme weather already causes problems (JMA 2018a): heavy rain and drought both cause a great deal of damage to crops every year. One way to reduce damage is to improve soil physical properties (Anzai 2016).

Soil physical properties in farmland are typically evaluated to a depth of about 20 cm in the topsoil and to about 60 cm in the subsoil. On-site measurement methods include the use of cylinder intake rate (Fukumoto 2013), disk permeameters (Perroux and White 1988), and infiltration meters (Reynolds and Elrick 1991, Savadogo et al. 2017) to evaluate permeability to water. However, they are slow, and water is needed.

Yamanaka System Hardness Sensors (Fujiwara Scientific Company, Japan) are commonly used in Japan for measuring soil hardness (Komatsu et al. 2007), and criteria for the diagnosis of

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soil hardness are often based on readings of these sensors. A study of 280 paddy field sites in Chiba prefecture found a positive correlation between the Yamanaka hardness index (YHI) values of soil compaction and the logarithm of penetration resistance measured by a cone penetrometer (Arihara and Watanabe 1993). However, to measure soil hardness with Yamanaka System Hardness Sensors, we have to dig a cross-section more than 60 cm deep. Since this takes time and effort, few cross-sections can be investigated in a day.

A cone penetrometer offers an easy and quick way to measure soil penetration resistance since it does not require special techniques or skills (EBSSAMM 1986). Since its measurements are continuous through the soil profile, it allows the soil bearing capacity, related to the running of tractors or combines, to be qualitatively evaluated, and the position of the plow layer to be determined from the irregular shape of the plot (EBSEAM 1997).

A DIK-5530 digital cone penetrometer (Daiki Rika Kogyo Co., Ltd., Kounosu, Saitama, Japan; Table 1) can display successive values of soil compaction in 1-cm increments to depths of up to 90 cm. With its Global Positioning System (GPS) receiver, it can record the location at the same time. Since it takes only 60 to 90 s per sampling, it is possible to collect data at more sampling points than with a Yamanaka System Hardness Sensor or by measuring water permeability within the same period. Soil physical properties differ even over short distances, so sampling at multiple points improves the resolution.

Systems for the automatic measurement of soil hardness have been developed (Carrara et al. 2007, Tekin et al. 2008, Fountas et al. 2013). Naderi-Boldaji et al. (2012) developed an on-the-go horizontal penetrometer using sensors mounted on tines drawn by a tractor. Being tractor drawn, the penetrometer can take measurements quickly with little effort. However, action of the tines destroys the soil structure, and continuous surveying is difficult. Since the plow pan plays an important role in paddy fields in preventing water leakage, it cannot be disturbed during sampling. As a cone penetrometer can be used simply by stabbing the rod below the ground surface, it can also be used to collect data with minimal disturbance.

Spatial statistics, geostatistical analysis, and spatial econometrics can be used to measure spatial variations (Mase 2010, Furutani 2011, Tsutsumi and Seya 2012, Seya and Tsutsumi 2014, Arbia 2016). Preparation for mapping can be facilitated through the use of a global navigation satellite system (GNSS). Current systems include the US Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), the European Union’s Galileo, and the Chinese BeiDou Navigation Satellite system. Regional navigation satellite systems include the Navigation Indian Constellation (previously Indian Regional Navigational Satellite System) and the Japanese Quasi-Zenith Satellite System (QZSS). The QZSS provides highly precise, GPS-compatible, stable positioning services in the Asia-Oceania region (Cabinet Office 2018).

As paddy fields have grown larger through field consolidation, guidelines for leveling precision have been devised for paddy field management. Judging from the optimal water depth for rice growth, Yamaji (1989) concluded that the target value of leveling precision was within a standard deviation (s.d.) of 20 mm. Technical documents provided by the Ministry of Agriculture, Forestry and Fisheries set target values of leveling precision for direct sowing of within s.d. = 12 mm on dry fields in cold regions, 15 mm on flooded paddy fields, and 20 mm on dry fields in warm regions (Oshita 2000). Through leveling by a 53.8-kW (73PS) tractor using a technique developed for automatic precision laser-leveling, in a 1-ha field, an elevation range of 16 cm was improved to ± 2.5 cm (s.d. = 1.58 mm) over 92% of the field (Kimura et al. 1999). In a study of the effect of unevenness in a paddy field on tiller development of direct-seeded rice in Niigata Prefecture, one laser-leveling operation improved the leveling precision from s.d. = 18 mm to 11 mm, and the proportion of measurement points within ±2.0 cm was increased from 80% to 94% (Sasaki et al. 2002). The annual use of a heavier tractor should improve leveling precision because soil hardness is not increased. In Yamagata prefecture, Seino et al. (1998) investigated secular changes of leveling precision in a 1.2-ha (200 m × 60 m) paddy field over 7 years. Leveling precision was maintained at s.d. = 9–16 mm, and the proportion of measurement points within ±2.0 cm reached 98.4%. Because spatial evaluation of a field requires a reference plane, variations in soil physical properties are best estimated when the height of the ground surface is regarded as 0 cm across the entire reference plane. Although precision can be a problem, being able to easily check the state of a field is effective in managing it.

This paper reports a study designed to develop a technique to enable the quantitative evaluation of soil hardness by cone pen-
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trometer for use in soil physical diagnosis. The study investigated time course changes in the 3D distribution of soil hardness and the effect of land leveling, and the effects of soil management on the distribution of soil hardness.

Materials and methods

3D distribution of soil hardness by cone penetrometer and GNSS receiver

The study used a DIK-5530 digital cone penetrometer (Table 1), which can measure from 245 to 2772 kPa. The DIK-5530 can acquire GPS signals. The GPS Standard Positioning Service’s Signal-in-Space User Range Error (URE) accuracy standard is < 7.8 m at 95% global average URE during normal operations over all ages of data, and < 6.0 m at 95% global average URE during normal operations at zero age of data (US Government 2008).

Methods developed for assessing measurement accuracy (Karsky 2004) show accuracies of 2 m for differential GPS and 1 cm for real-time kinematic GPS (Sabatini and Palmerini 2008). However, these methods need expensive devices and advanced expert knowledge (Trimble Navigation 2003). In contrast, simplicity and low cost are required for widespread adoption of GNSS technology for soil testing. The eTrex 30 navigator (Garmin, Olathe, KS, USA) is affordable, and can detect multiple GNSS (including QZSS) and GLONASS satellites. Although positioning error is reduced as the number of visible satellites increases, the ideal number of GPS satellites is not always visible (Cabinet Office 2018).

The eTrex 30 can immediately record the location of the sampling points. However, since its mesh positioning is not accurate, the number of samples acquired can vary by survey. Preliminary experiments showed that differences can be minimized as long as 60 or more locations are surveyed per hectare (data not shown).

Creating 3D distribution maps of soil hardness in a field

Figure 1 shows a schematic diagram of a method for generating 3D distribution maps of soil hardness in a 1-ha field surveyed at 10-m intervals with the DIK-5530.

The height of the ground surface was regarded as 0 cm across the fields, which the farmers leveled every year. At each sampling point, the GNSS receiver records the latitude and longitude and the penetrometer records soil hardness at 1-cm intervals to 60 cm depth by conducting a sampling each survey. The data from the DIK-5530 are sorted by macro in Microsoft Excel and plotted as a set of 60 contour maps in Origin Pro 2018b software (OriginLab, Northampton, MA, USA), which are saved to a Microsoft PowerPoint file. Data processing for one field takes less than 10 min.

Because soil physical properties are highly dependent on the survey point, more points are better. In this study, soil hardness was surveyed at 60 to 108 points per hectare, up to 20 times the number of survey points in a conventional survey.

Experimental design

Experiment 1: Changes in 3D distribution of soil hardness in Field Y over 1 year

The change in the 3D distribution of soil hardness over 1 year was investigated in Field Y, which belongs to the Agricultural Union Corporation Miyazaki Collaboration, Yuki City, Ibaraki pref., Japan (36.279°N, 139.893°E). The farm size is about 100 ha. The soil is classified as a Typic Fluvaquent (Soil Survey Staff 2014) or a grey alluvial soil (5CSCN 2017). Field Y is rectangular and covers 1 ha. A feed-rice-wheat-soybean-wheat rotation was
conducted for 2 years. Wheat and soybean were harvested with a 190-kW combine (11.7 Mg, 7800 L grain capacity), and the whole feed-rice crop was harvested with a chopping harvester (4.5 Mg, 55 kW). Four 70- to 86-kW tractors (3.3 to 5 Mg) work the farm.

Soil hardness was surveyed 4 times: on 2015/11/15 (after rice harvest, before wheat sowing, 81 points, Y1), 2016/3/2 (during wheat, 60 points, Y2), 2016/6/1 (around wheat harvest, before soybean sowing, 64 points, Y3), and 2016/11/18 (after soybean harvest, before wheat sowing, 89 points, Y4) (Table 2). The same points were sampled each time with reference to a map and the eTrex 30 on a mesh of 10 to 15 m for consistency between sampling dates.

To test any association among soil hardness values at each depth, the horizontal patterns of soil hardness were analyzed by hierarchical cluster analysis in R v. 3.5.1 software (R Core Team 2018), using Ward’s method. On the assumption of 1 or 2 plow layers, a plow pan, and the subsoil, there would be 3 to 6 clusters. Two patterns were analyzed. Seasonal comparison used all raw data. Annual comparison analyzed data of 60 sampling points in almost the same positions on 2015/11/25 (Y1) and 2016/11/18 (Y4).

### Table 2 Cultivation history of Field Y from 2015/6/22 to 2016/11/26, and numbers of the sampling points and survey time in Survey Y1, Y2, Y3 and Y4.

| Crop    | Operation/Survey       | Date            | Numbers of sampling points (points) | Survey time (min.) |
|---------|------------------------|-----------------|-------------------------------------|--------------------|
| Rice    | Transplanting          | 2015/6/22       |                                      |                    |
|         | Harvest                | 2015/10/15      |                                      |                    |
|         | Bottom plowing (Plowsoiler) | 2015/10/Mid     |                                      |                    |
|         | Rotary tilling         | 2015/11/Early   |                                      |                    |
|         | Leveling               | 2015/11/Mid     |                                      |                    |
|         | Survey Y1              | 2015/11/25      | 81                                   | 88                 |
| Wheat   | Sowing (Drill seeder)  | 2015/11/25      |                                      |                    |
|         | Survey Y2              | 2016/3/2        | 60                                   | 73                 |
|         | Survey Y3              | 2016/6/1        | 64                                   | 273*               |
|         | Harvest                | 2016/6/14       |                                      |                    |
|         | Rotary tilling         |                 |                                      |                    |
| Soybean | Sowing (Drill seeder)  | 2016/7/4        |                                      |                    |
|         | Harvest                | 2016/11/17      |                                      |                    |
|         | Survey Y4              | 2016/11/18      | 89                                   | 93                 |
| Wheat   | Sowing (Drill seeder)  | 2016/11/26      |                                      |                    |

*including surface soil sampling and yield survey at each sampling point

### Table 3 Cultivation history of Field I from 2015/10/4 to 2016/4/12, numbers of sampling points, and survey times in Surveys I1 and I2.

| Crop    | Operation/Survey       | Date            | Numbers of sampling points (points) | Survey time (min.) |
|---------|------------------------|-----------------|-------------------------------------|--------------------|
| Rice    | Harvest                | 2015/10/4       |                                      |                    |
|         | Survey I1              | 2015/10/5       | 101                                 | 88                 |
|         | Bottom plowing         | 2016/1/Early    |                                      |                    |
|         | Rotary tilling         | 2016/3/Mid      |                                      |                    |
|         | Leveling               | 2016/3/31       |                                      |                    |
|         | Survey I2              | 2016/4/12       | 108                                 | 121                |

### Table 4 Specifications of tractor and laser leveler.

| Tractor                  | Manufacturer | New Holland |
|--------------------------|--------------|-------------|
| Type                     | T6020        |             |
| Weight (Mg)              | 5.22         |             |
| Length (m)               | 4.28         |             |
| Width (m)                | 2.35         |             |
| Height (m)               | 2.99         |             |
| Gross, power (kW)        | 82           |             |

| Laser leveler            | Manufacturer | Sugano |
|--------------------------|--------------|--------|
| Type                     | LL4000       |        |
| Weight (Mg)              | 1.29         |        |
| Length (m)               | 2.16         |        |
| Width (m)                | 2.44         | 4.19 (working width) |
| Height (m)               | 2.65         |        |

### Experiment 2: Effect of land leveling on 3D distribution of soil hardness in Field I

The 3D distribution of soil hardness was investigated in paddy Field I, which belongs to the Minami-Ota Farming Union, Inashiki City, Ibaraki pref. (35.888°N, 140.314°E), on 2015/10/4 (after rice harvesting, before leveling, 101 points, I1) and on 2016/4/12 (after leveling, 108 points, I2).

The farm size is about 50 ha. Rice was harvested with an 81-kW combine (4.4 Mg, 2000 L grain capacity). One 81-kW and two 40-kW tractors (4 to 5.5 Mg) work the farm. The soil is classified as a Typic Fluvaquent (Soil Survey Staff 2014) or grey alluvial soil (5CSCN 2017). Comparison of the results allowed the effect of leveling on the 3D distribution of soil hardness to be evaluated.

The soil in the 1-ha field took 4 h to level on 2016/3/31 (Table 3) with the tractor and laser leveler shown in Table 4. The route...
during leveling was recorded with an eTrex 30.

As in Experiment 1, 3D-distribution maps of soil hardness were created, and the average and s.d. of soil hardness by depth before and after leveling were plotted. Although the total weight of the equipment (~6.5 t) and the length, width, tire position, and wheel base are known (Table 4), and speed and acceleration during leveling can be calculated from the GNSS data, methods to estimate soil compaction have not been developed yet, so the degree of soil compaction cannot yet be calculated. The field was divided into a 10-m mesh, and the number of tractor passes was recorded.

Experiment 3: Difference between direct-sowing and transplanting of rice on 3D distribution of soil hardness

This experiment compared the effects of field management on soil hardness. Field I grew Koshihikari rice, a popular cooking rice (Exp. 2), direct-sown by drill seeder (no-tillage). Field Y grew a crop rotation, including Yumeaoba rice, a feed rice (Exp. 1), transplanted by rice planter. To compare soil hardness under similar conditions, the fields were surveyed after harvest (harvests I1 and Y1). Since Yumeaoba was transplanted in June and harvested after the Koshihikari harvest had finished, Field Y was harvested about 50 days later than Field I.

Results and Discussion

Experiment 1: Changes in 3D distribution of soil hardness in Field Y over 1 year

Measurement took 88 min at Y1 (n=81), 73 min at Y2 (n=60), 273 min at Y3 (n=64) (including surface soil sampling and yield at each point), and 93 min at Y4 (n=89). Representative contour plots of soil hardness are shown in Figure 2-1, 2-2 and 2-3. Since the plow pan was evident in the range from 10 to 20 cm, contour plots from 10 to 20 cm are shown in 2-cm increments.

The average and s.d. of soil hardness by depth are plotted in Figure 3. Although the absolute values changed over time, the tendency of each was consistent: there was a bulge of s.d. (peak, 15 cm; range, 9–20 cm) in all plots, which corresponded to a rapid increase in the average.

In guidelines for soil diagnosis in each prefecture, reference values are often <20 mm on the YHI (MAFF 2016b). Regression curves that relate penetration resistance to the YHI from prefectural guidelines that present them are shown in Figure 4. Older units of kg cm⁻² are converted to kPa. Root growth is inhibited and permeability to water is very poor in all soils at 20 to 22 mm on the YHI, even though the values of solid-phase ratio or bulk density depend on soil type (Saegusa 1997). In humic Andosols, 1500 kPa measured by cone penetrometer is equivalent to 20–21 mm on the YHI (EBSEAM 1997). The range of soil hardness that inhibits root growth and moisture permeability in this study ranged from 1300 to 2500 kPa (Fig. 4). When YHI > 20 mm (>1300 kPa, Fig. 4), the steepness of the regression curve makes it hard to assess the magnitude of the soil hardness quantitatively. Use of the cone penetrometer, in contrast, makes it possible to locate the plow pan.

These results show that plots of s.d. can accurately locate the depth range in which the plow layer grades via the plow pan into the subsoil. The plow pan marks the boundary zone between the plow layer and the subsoil. When the s.d. values are increasing, patches of harder soil begin to appear in the field. After reaching the maximum, s.d. decreases again as hardness becomes more uniform. The peak of the bulge is taken to mean the beginning of the plow pan. The inflection point in all seasons was 15 cm, the likely depth of the rotary blade.

Values of the YHI increase linearly with decreasing soil water content (Yamanaka and Matsuo 1962). Thus, a higher soil moisture content improves plasticity and reduces soil hardness. November had relatively high rainfall in both 2015 and 2016 (Figure 5). This explains why the average soil hardness at Y4 (after soybean) was the lowest of all surveys. Kamiyama et al. (2012) surveyed water requirement, percolation rate, and soil hardness under various soil water conditions at various compaction strengths to see how to reduce field permeability of soil growing direct-seeded rice. Soil hardness decreased in the order of low soil water content/high compaction > high soil water content/high compaction > high soil water content/low compaction. Although the relationship between soil hardness and precipitation must be clarified, the average soil hardness of Y1 and Y4 might be relatively low.

Soil moisture content changes with both location and depth in the field, and therefore soil hardness does too. Values measured by cone penetrometer cannot separate the effect of soil hardness due to dryness and softness due to plasticity (Yamanaka and Matsuo 1962). Softer points than surrounding points might have a higher moisture content.

Although the absolute values of soil hardness depended on the season, hardness tended to be higher at the field margins than in the middle of the field (Fig. 2-1, 2-2 and 2-3), likely owing to the regular use of heavy machinery to work the headland.

To investigate how the horizontal distributions of soil hardness per 1 cm depth were grouped, hierarchical cluster analyses were performed for each season (Figure 6). The horizontal distributions were separated into two groups (1–14 or 15 cm and ≥15 or 16 cm) in all seasons. The 1–14- or 15-cm group was subdivided into 1–9 or 10 cm and ≥10 or 11 cm, effectively the plow layer and the boundary zone between there and the plow pan, respectively. The >15- or 16-cm group tended to be subdivided into ~15–20 cm and >20 cm, effectively the plow pan and the subsoil layer, respectively. These groupings did not change notably throughout the year.

To investigate the differences in the horizontal distributions of soil hardness per 1 cm depth before and after plowing, cluster analysis was conducted with the Y1 and Y4 data (Figure 7), which
correspond to wheat cultivation. The horizontal distributions were separated into two groups (1–19 or 20 cm and ≥20 or 21 cm) in both years. The 1–19 or 20-cm group was subdivided into 1–12 or 13 cm and ≥13 or 14 cm, effectively the plow layer and plow pan, respectively. This cutoff (~19 or 20 cm) was deeper than that in the seasonal comparison (~13 or 14 cm) because of the better alignment of the sampling points. As a result, the plow pan was grouped with the plow layer. Because the plow pan is near the boundary zone, the classifications were slightly different. However, the groups remained the same in each year and were in substantially the same position.

The constancy of the relative positions of hard and soft patches throughout the year, the detection of the plow pan at around 15 cm on all dates, and the results of cluster analyses show that a cone penetrometer can be used for quantitative evaluation of soil hardness at any time of the year. Although the height of the ground surface was set as 0 cm each time, the depth of the plow pan did not change (Fig. 3), likely because the ground level was maintained through regular soil leveling and the land use as a paddy field.

Experiment 2: Effect of land leveling on 3D distribution of soil hardness in Field I

Measurement took 88 min in I1 (n=101) and 121 min in I2 (n=108).

The locations of sampling points before and after soil leveling are shown in Figure 8. The route of the leveler shows that all four sides of the field received multiple passes, in particular the right-hand side. In direct-seeded paddy fields, leaks in the levees are
easy to see (Kanmuri et al. 2012). As this field has drainage points on the right-hand side, it is possible that the operator paid careful attention to leveling so as to stop all leaks.

The number of tractor passes was integrated into the 10-m mesh in Figure 9. The number ranged from 16 to 74, with an average of 29.6 and a median of 25. Nearly 2/3 of the field (65%) received 16 to 30 passes. The right-hand side of the field received many passes. As the laser leveler is wider than the tractor (Table 4), some areas might have received even more.

Representative contour plots of soil hardness in Field Y before and after land leveling are shown in Figure 10-1, 10-2 and 10-3. To separate the influence of the first cultivation, differences were also plotted. As in Experiment 1, although the absolute values of soil hardness depended on leveling, the hardness tended to be higher on the field margins than in the middle. In the difference plots, the plow layer (<16 cm) was most affected by compaction during leveling, especially on the right-hand side of the field. In the range of the plow pan (16–21 cm), the effects of compaction remained at the upper-right side (Fig. 10-1, 10-2 and 10-3). As the field drainage is placed along this side, the results show the extra work by the tractor.

The average and s.d. of soil hardness by depth are plotted in Figure 11. The s.d. shows a bulge (peak, 16 cm; range, 11–21 cm) in both fields. After leveling, there was another bulge (peak, 2 cm; range, 1–9 cm), likely due to increased compaction of the surface layer by the leveler. Since soil is leveled when dry, the compaction
was not transmitted to the subsoil. As judged from the increased average soil hardness from 3 to 16 cm, soil compaction remained in the plow layer. At the position of the s.d. bulge, the increased soil hardness masked the presence of the plow pan.

The s.d. plots were evaluated more precisely to estimate the possibility that the reference plane had been lowered by leveling. In I1 (before leveling), bulges peaked at 3, 16, and 24 cm; in I2 (after leveling), bulges peaked at 2, 16, and 27 cm (Fig. 11). If the
reference plane goes down owing to leveling, the position of the peaks should go up. Thus, there was almost no influence down to the plow pan by a drop of 1 cm on the soil surface.

Experiment 3: Difference between direct-sowing and transplanting of rice on 3D distribution of soil hardness

The effects of differences in field management methods on the 3D distribution of soil hardness were compared between Field Y (Y1 in Fig. 2-1, 2-2 and 2-3) and Field I (I1 in Fig. 10-1, 10-2 and 10-3). In Field I, soil hardness ranged from 337.5 to 675.0 kPa from 4 to 60 cm with no sudden increase with depth. Although the field margins were compacted to prevent leakage, no hydroponic soil layer could be seen. In Field Y, soil hardness ranged from 0 to 1013.0 kPa to 10 cm, and was softer than in Field I. But from 15
cm, the plow pan could be seen, and soil hardness increased to 25 cm and remained high to 60 cm. The contrast in soil hardness from the surface soil via the plow pan into the subsoil was greater in Field Y than in Field I.

Comparison of Y1 in Figure 3 with I1 in Figure 11 shows that the distributions of soil hardness were affected by the planting method. In Field Y, the average values of soil hardness in the subsoil were all larger than the overall average, and soil hardness increased rapidly from the plow layer via the plow pan to the subsoil. The plot of s.d. shows a distinct bulge. In Field I, in contrast, the average values of soil hardness in the subsoil were close to the overall average, and soil hardness increased only slightly at the base of the plow pan. In both fields, peaks at 15 or 16 cm in the plot of s.d. mark where the rotary blade strikes.

![Fig. 5 Changes in precipitation from 1 June 2015 to 1 December 2016 collected near Field Y by Automated Meteorological Data Acquisition System (Shimodate; JMA 2018b).](image)

![Fig. 6 Results of hierarchical cluster analyses based on the horizontal distribution of soil hardness at each 1-cm depth in each season in Field Y.](image)
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Fig. 7  Results of hierarchical cluster analysis based on the horizontal distribution of soil hardness at each 1-cm depth in Field Y at dates Y1 and Y4.

Fig. 8  Relationships between the sampling points of I1 and I2, and route taken during land leveling in Field I. Aerial photography by Geographical Survey Institute, 2010/05/01. The upper 1 ha of this field is not shown.

Fig. 9  Tractor passes by analysis of Land leveling in Fig. 8: route taken during land leveling in Field I.
Since puddling of the soil blocks soil pores with fine particles, the water is less likely to leak in transplanting culture, and the plow pan develops harder. On the other hand, direct sowing involves only pressing on the soil surface, and a plow pan doesn’t develop, so the subsoil is little affected by the pressure.

Kanmuri et al. (2012) showed that three-step compaction of the field surface steadily reduced the irrigation water requirement to 20 mm/d. To achieve this condition, the soil hardness at 5 cm depth must be about 20 mm on the YHI or water cannot pass. As shown in I2 in Figure 11, the soil hardness at around 2 cm depth was
greater after leveling. In the case of direct-sowing, it is therefore important to harden the soil surface so as to prevent leakage.

This method was thus able to quantitatively evaluate the impact of the difference in planting method on soil hardness.

Fig. 10-2  Relationship between sampling point and field position, representative contour plots of soil hardness at I1 and I2, and differences (I2–I1) at depths of 14, 16, 18 and 20 cm.

**Conclusions**

The most important result of this study is that the 3D distribution of soil hardness in the field can be mapped much more quickly through the use of a cone penetrometer than by conventional tech-
Fig. 10-3 Relationship between sampling point and field position, representative contour plots of soil hardness at I₁ and I₂, and differences (I₂–I₁) at depths of 30, 40, 50, and 60 cm.

Techniques. If the soil hardness is measured to 60 cm depth, one person can survey 1 ha in 90 min and can thus screen a wide range of fields in a short time.

The results of the cluster analysis of the horizontal distribution of soil hardness show that this methodology can be used to measure soil hardness at any time of the year. However, because the absolute values of soil hardness vary with the season, the most effective use of a cone penetrometer is to cover the entire field.
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As differences in the distribution of soil moisture content can bias results, further studies should investigate the relationships of soil hardness with soil moisture content and with rainfall quantity and quality.

Plotting of the average and s.d. of soil hardness by depth could identify the position of the plow pan and reveal the effects of land leveling.

Differences in the distribution of soil hardness revealed the effects of field management on soil hardness. In particular, plotting the s.d. of soil hardness revealed differences in the position and structure of the pan. This methodology can also measure the effects of large machinery. For part of this study, a patent was applied for in August 2017.

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Fig. 11 Distributions of average and standard deviation (s.d.) of soil hardness by depth in Field I.
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