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# Effect of Roots on Formation of Internal Fissures in Clayey Paddy Soil during Desiccation

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**Abstrct**

Internal fissures in clayey soil are important for tillage efficiency. The roots reinforce the soil and absorb soil moisture, resulting in shrinkage and fractures in the massive soil structure. The objective of this study is to clarify the influence of roots on the prevention of wide cracks and the formation of small fissures during desiccation. Soil samples were taken from the surface layer of inter-row spaces of a clayey paddy three weeks after the release of ponding water in the summer 1998. In half of the sampling sites, the stems and leaves of the rice plants were cut away just before the release of the ponding water, in order to compare the effects of the two resulting water absorption conditions. After measurement of the volume fractions of the solid, liquid, and air phases, the oven-dried samples were soaked in water and then scoured with tap water in a sieve. The remaining roots were dried and weighed. The relationships among volumetric air ratio, moisture ratio, and root density were statistically analyzed, with the volumetric air ratio being regarded as the ratio of newly formed fissures due to desiccation. Positive direct correlations were observed between root density and air ratio for all plots. In the plots with transpiration, since the moisture ratio correlated with root density and air ratio, a large proportion of the variances in air ratio explained by moisture ratio and root density were shared. These results lead to the following conclusion : Rice plant roots inhibit the formation of wide cracks and induce small fissures in clayey well-puddled soil during desiccation. With transpiration, these effects are attributed to the compound functions of roots : absorption of water and soil reinforcement. However, even without transpiration, soil reinforcement by roots uniquely contributes to the development of small fissures.

**Key words** : Soil shrinkage, Root density, Internal fissure, Soil reinforcement, Absorption of soil moisture

## 1. Introduction

Internal micro-cracks in soil are practically important for tillage efficiency, because soil's tensile strength depends on the number and extent of fissures from which fractures would begin. Utomo and Dexter (1981) proposed that the friability of soil clods can be expressed by the linear relationship between the logarithm of aggregate volume and the logarithm of tensile strength. The slope of the relationship is a measure of the dispersion of the strengths of micro-cracks and flaws. Major processes in the formation of aggregates in soils are desiccation, shear failure, and biological activity (Wilding and Hallmark 1984). Micro-cracks in soil are also considered to be formed by the combination of such factors or by previous tillage.

Desiccation causes soil shrinkage and brings the particles closer together, but if the movement of soil particles is constrained, tensile stress is generated between the particles, resulting in tensile failure. The shrinkage characteristic of soil depends not only on the properties of the soil, but also on the rate of desiccation or substances that hinder the homogeneous movement of soil particles. Roots in soil exert large effects on soil shrinkage behavior, because they increase the rate of desiccation and reinforce the soil. Mitchell and van Genuchten (1993) clarified the effects of roots on an *in situ* soil shrinkage rate. After observing greater shrinkage volume in fallow fields than in wheat and alfalfa fields, they concluded that soil's shrinkage characteristic may change, depending on the cropping condition.

Waldron *et al*. (1983) measured the shear resistance of soil reinforced by alfalfa and pine roots, and observed a significant increase compared to the soils without roots. Waldron and Dakessian (1981) measured the mechanical properties of roots, and related them to increased soil shear resistance. Their analysis showed that the elastic behavior of roots enhances resistance against the shear stress. Thus, it is naturally deduced that roots also increase the tensile strength of soil, and inhibit homogeneous shrinkage.

The effects of roots on soil's shrinkage behavior include not only reinforcement but also water absorption. It should be noted that roots reinforce the soil against the tensile stress generated by the depletion of water, which the roots themselves cause. Yoshida et al. (1997) pointed out that the introduction of winter crops into paddy fields enhances the macropores in soil in spring, when the crops begin to grow again. Pillai and McGarry (1999) compared the effect of crops on the structural repair of compacted soil. They concluded that lablab [*Lablab purpureus* (L.) Sweet] and mung bean [*Vigna radiata* (L.) R. Wilezek] lead to the rapid repair of soil structures due to the great cyclic variation in wetting and drying induced by a large evapotranspiration rate. These studies suggest that the absorption of water by roots may also contribute to the formation of soil structure because roots inhomogeneously distribute suction and tensile stress, possibly inducing micro-cracks.

The present study examines the relationship between the internal fissures and root density with respect to water content, aiming to discriminate between the two different effects of roots on soil shrinkage : water absorption and soil reinforcement. Such discrimination is practically useful to estimate the difference between the effects of living and remaining roots on soil structure during desiccation.

## 2. Materials and Methods

The experimental paddy field used for this study is located at the Hokuriku Agricultural Experiment Station in Niigata Prefecture, Japan. It has been utilized as an irrigated paddy for more than 20 years. The soil is clayey, montomorillonitic, mesic, typic Epiaquepts, and contains 38% clay, 37% silt, and 25% sand. The experiment was performed in 1998. The rice seedlings were transplanted in rows by hand from scaffolds that had been set up around and across the sample site in order to avoid disturbing the surface of the soil. The row spacings were set as 30 cm or 60 cm. The ponding water was maintained on the surface of the field until 11 August 1998. In half of the sampling sites, the stems and leaves of the rice plants were cut away just before the release of the ponding water, in order to compare the effect of water absorption on soil shrinkage behavior. In these sites, only the roots, which hardly absorb water, remained in the soil. Sampling of the soil was performed on 10 and 11 September. Undisturbed core samples, each with a diameter of 50 mm and a thickness of 25 mm, were taken from the surface layer in the inter-row space, avoiding the wide visible cracks. The distances from the plants were referred to in determining the sampling sites, since samples with large deviations in root density were desirable for the analysis. After measuring volume fractions in the solid, liquid, and air phases, the oven-dried samples were soaked in water for a day and then scoured with tap water in a sieve with a 0.42-mm mesh. The remaining roots were picked up, dried for 24 hr. in an oven at 85℃, then weighed.

## 3. Results and Discussion

Figure 1 provides a typical shrinkage characteristic curve, representing decreasing soil void ratio with decreasing soil moisture ratio. The structure of the well-puddled paddy soil shows little stability. Most of the pores are plastic and shrink easily within the stress range induced by low suction. Thus the entry of air into stable macro-pores, usually observed in structured soils (a), is negligible for puddled clay soils (b, c). In the normal shrinkage range, cracks or small internal fissures are easily produced in the in situ puddled soils (b), while in the conventional shrinkage tests in the laboratory, puddled samples packed in the testing dishes exhibit volume decreases that are almost equal to the water losses (c). This is because the horizontal movement of soil is not allowed in the fields but is allowed in the laboratory test. The formation of cracks or many small fissures is the only process in which the increasing horizontal stress is released. At a higher suction range, soil exhibits residual shrinkage or zero shrinkage. These shrinkage regimes are relatively less important for the formation of structures, since the entry of air into pores precedes the deformation of pores. In soils reinforced by many roots, crack formation tends to be inhibited and instead small fissures are induced. To compare the effect of roots on such fissures induced by desiccation, we used the volumetric ratio of air with respect to the volume of a solid, assuming that all the air-filled pores are newly made by fractures. This hypothesis seems to be reasonable because the puddled pasty clayey soil never initially has large stable pores subject to air entry, due to low suction. The pores between larger clods would be filled with small particles during the sedimentation process after puddling.

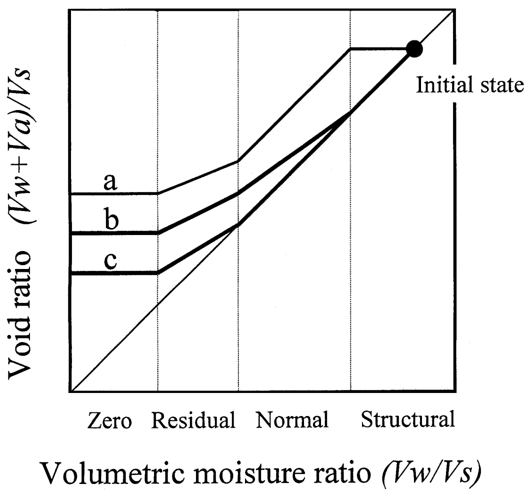



**Fig. 1** Typical shrinkage characteristic curves for (a) structured non-swelling soils, (b) well-puddled swelling soils *in situ*, and (c) well-puddled swelling soils in conventional shrinkage tests.

Fig. 2 (a) through (c) show the relationships among root density, volumetric moisture ratio (Vw/Vs), and volumetric air ratio (Va/Vs) for the samples in the plots with transpiration. According to the shrinkage characteristic observed in the disturbed samples of the same field, the maximum and minimum moisture ratios of 2.2 and 1.3 shown in Fig. 2 correspond approximately to suction levels of 1 kPa and 100 kPa, respectively. All the samples are therefore considered to be within the normal shrinkage range. Negative significant correlations are observed between volumetric moisture ratio and volumetric air ratio (a) and between root density and volumetric moisture ratio (c) ; and a positive significant correlation is observed between root density and volumetric air ratio (b). The negative correlation between moisture ratio and air ratio, shown in (a), can be naturally accepted by regarding typical shrinkage characteristics discussed in the preceding section : the increase in air ratio, representing the formation of internal fissures, is induced by a decrease in the moisture ratio, in other words, 'desiccation'. On the other hand,

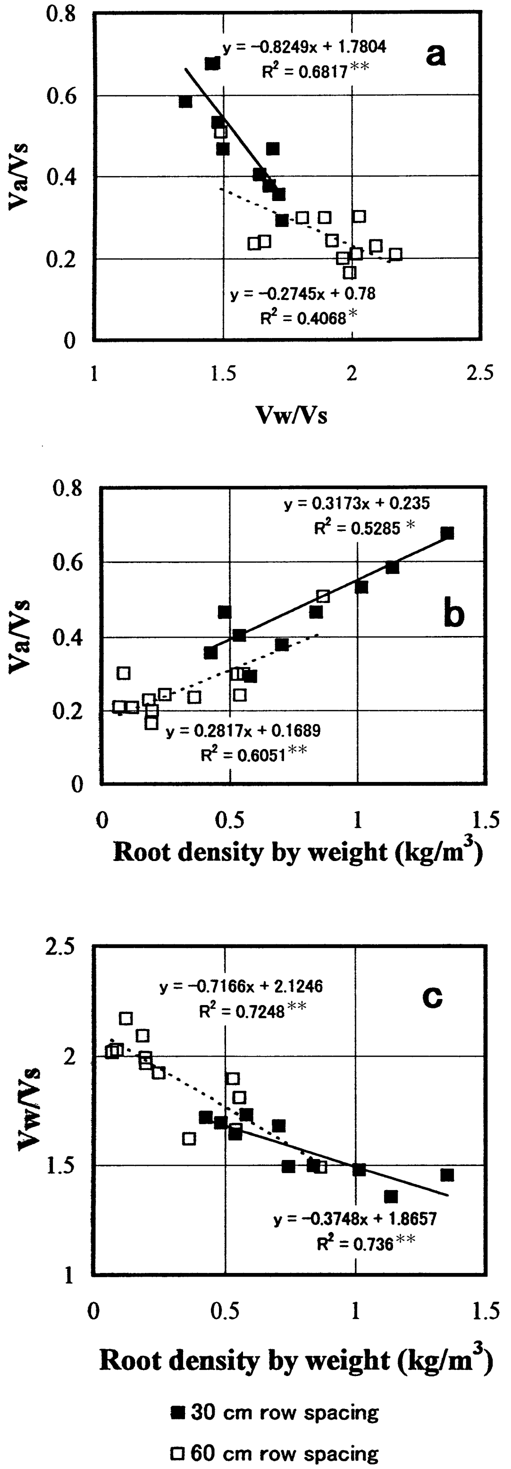



**Fig. 2** Relations between (a) volumetric moisture ratio (Vw/Vs) and volumetric air ratio (Va/Vs), (b) root density and volumetric air ratio (Va/Vs), and (c) root density and volumetric moisture ratio (Vw/Vs) for the samples in the plots with transpiration.
*, ** : Significant at the 0.05 and 0.01 probability levels, respectively.

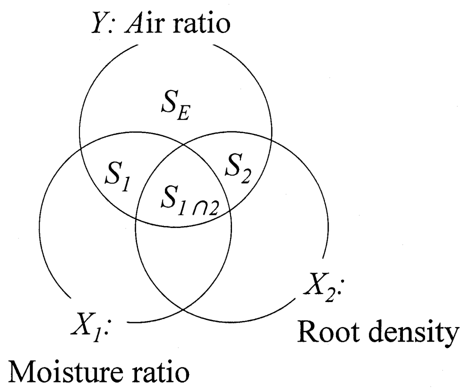



**Fig. 3** Concept of shared and unique variance explained by two inter-correlated factors.

the positive correlation between root density and air ratio does not necessarily demonstrate that roots mechanically reinforce the soil resulting in the formation of fissures by shrinkage, because roots simultaneously reduce the moisture ratio, resulting in the observed increase in the air ratio. Thus we should delineate the effect of root density on air ratio by calculating the unique and shared variances between these independent variables. The concept is summarized in Fig. 3 after Hair et al. 1998. The total variance in the volumetric air ratio consists of the variance uniquely explained by moisture ratio ($S_1$), the variance uniquely explained by root density ($S_2$), the variance explained jointly by both factors ($S_{1\cap 2}$), and the variance not explained by these factors, i.e., error ($S_E$). The procedure of calculation is provided in the Appendix. The results are shown in Table 1. All these variances are calculated for the standardized data : the total variance in the air ratio is equal to one, and the

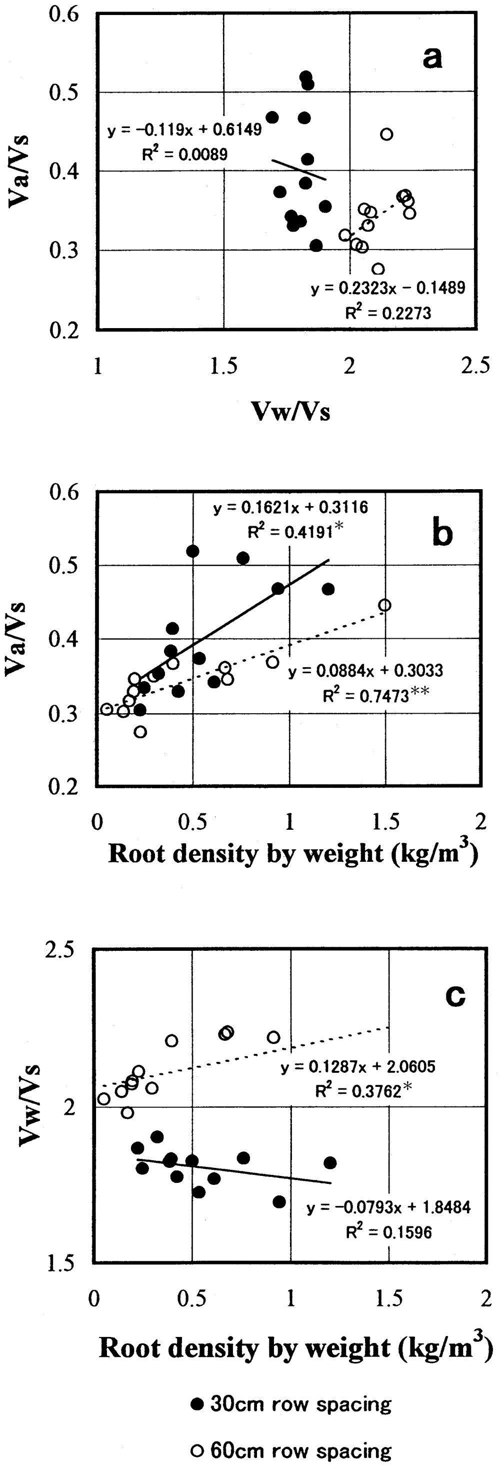
**Table 1** Direct correlation coefficient between the variables and composition of variances of standardized Va/Vs (With Transpiration)

| | | | Volumetric moisture ratio (Vw/Vs) | Root density |
|---|---|---|---|---|
| 30 cm row spacing | *R* : Direct correlation coefficient | Air ratio (Va/Vs) | −0.8257** | 0.7270* |
| | | Volumetric moisture ratio (Vw/Vs) | — | −0.8579** |
| | Variances of standarized Va/Vs | ($S_1$) : Unique variance explained by Vw/Vs | 0.1546 | |
| | | ($S_2$) : Unique variance explained by root density | 0.0013 | |
| | | ($S_{1\cap 2}$) : Shared variance | 0.5272 | |
| | | ($S_{1\cap 2}$) : Total variance explained by these factors | 0.6830 | |
| | | | Volumetric moisture ratio (Vw/Vs) | Root density |
| 60 cm row spacing | *R* : Direct correlation coefficient | Air ratio (Va/Vs) | −0.6378* | 0.7779** |
| | | Volumetric moisture ratio (Vw/Vs) | — | −0.8513** |
| | Variances of standardized Va/Vs | ($S_1$) : Unique variance explained by Vw/Vs | 0.0022 | |
| | | ($S_2$) : Unique variance explained by root density | 0.2004 | |
| | | ($S_{1\cap 2}$) : Shared variance | 0.4047 | |
| | | ($S_{1\cap 2}$) : Total variance explained by these factors | 0.6073 | |

*,** : Significant at the 0.05 and 0.01 probability levels, respectively.

total variance explained by factors ($S_{1\cap 2}$) is identical to the coefficient of determination ($R^2$) after the multivariate analysis. It should be noted that the shared variance is substantial compared to the unique variances of the factors. Therefore, while the roots absorb soil moisture, the compound function of roots : water absorption and reinforcement, is exerted on the increase in internal fissures during shrinking. The variances not explained by these factors may include experimental errors and effects of unknown variation in properties of the soil or the roots.

Fig. 4(a) through (c) show the relationships between the factors for the samples in the plots without transpiration. No correlations were observed between moisture ratio and air ratio ; however, positive significant correlations between root density and air ratio were observed. Although the moisture ratio is slightly correlated with root density in the 60 cm row spacing plot, this might be due to the difference in drainage efficiency between the row and the row-middle, and has no significant meaning. Thus we regard that no correlations exist between the root density and the moisture ratio in the following discussion. The significant positive correlations between root density and air ratio without the effect of moisture ratio prove that the mechanical reinforcement of the roots induces small fissures after desiccation even when the roots do not absorb soil moisture. In other words, during desiccation due solely to evaporation, roots mechanically induce internal fissures in soil by meshing and fixing the soil particles together, against the




fracturing forces generated by shrinkage.

The effect of root density on the increase in air ratio is considerably less in the plots without transpiration than in the plots with transpiration, according to the slope of the relationship shown in Fig. 2(b) and Fig. 4(b). Therefore, the effect of roots on the development of friable structures of soil is better exerted during the period when rice plants actively transpire. However, these findings may also aid in controlling the structure of clayey soils after harvesting rice. If the roots remain until the next spring and become enmeshed in the soil, they can contribute to the creation of fissures as the soil dries. The clayey paddy soil just after rice harvesting is so sticky that large clods would be produced if tillage were performed then. Such clods would shrink with few internal fractures the next spring, becoming extremely hard with poor friability. If no mechanical procedures are performed until the next spring, many fissures can be naturally produced as the soil dries.

The increase in the volume of minute fissures depresses the development of wide cracks. These findings therefore suggest that root density controls the distribution of the total shrinkage volume to the wide cracks and small fissures. Root density varies with respect to the distance from the plant. The regions in which roots extend sparsely are subject to wide cracks, while the regions near the plants are not. Soil reinforcement by roots also affects the cracking patterns between the rows in this manner.

**Fig. 4** Relations between (a) volumetric moisture ratio (Vw/Vs) and volumetric air ratio (Va/Vs), (b) root density and volumetric air ratio (Va/Vs), and (c) root density and volumetric moisture ratio (Vw/Vs) for the samples in the plots without transpiration.
*, ** : Significant at the 0.05 and 0.01 probability levels, respectively.

## 4. Conclusion

The roots of rice plants inhibit the formation of wide cracks and induce small fissures in clayey well-puddled soil during desiccation. This effect of roots on soil is exerted even when the roots do not absorb soil moisture. This finding is important in regard to the physical function of the roots that remain after crops are harvested.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## **Appendix** (after Hair *et al.* 1998)

The analyst can determine the shared and unique variance for inter-correlated independent variables using direct correlation coefficients. Part correlation of $Y$, $X1$, given $X2$ can be calculated as :

$$r_{Y,\,X1(X2)}=\frac{r_{Y,\,X1}-(r_{Y,\,X2}\times r_{X1,\,X2})}{\sqrt{1-r_{X1,\,X2}{}^2}} \quad (1)$$

where $r_{a,b}$ denotes a direct correlation coefficient between variables $a$ and $b$ ; and $Y$ denotes the dependent variable. $X1$ and $X2$ denote independent variables, inter-correlated with each other. The unique standardized variance predicted by $X\,1$ is equal to the square of the part correlation :

$$S_1=r_{Y,\,X1(X2)}{}^2 \quad (2)$$

The unique variance explained by $X2$ is also written as :

$$S_2=r_{Y,\,X2(X1)}{}^2 \quad (3)$$

The amount of shared variance can be confirmed by subtracting the standardized unique variance from the square of the direct correlation coefficient between Y and $Xi$ :

$$S_{1\cap 2}=r_{Y,\,X1}{}^2-S_1 \quad (4)$$

or

$$S_{1\cap 2}=r_{Y,\,X2}{}^2-S_2 \quad (5)$$

Both equations lead to the same result. The summation of these variances yields total variances explained by these independent variables :

$$S_{1\cup 2}=S_1+S_2+S_{1\cap 2} \quad (6)$$

This value exactly corresponds to the coefficient of determination $R^2$ after the performance of multivariate analysis.

# 粘質水田土壌の乾燥による内部微細亀裂の発生に対する根系の影響

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土塊内部に潜在する小ひびは，易耕性に重要な役割を果たしている。代かきが行われた粘土質水田土壌では，乾燥収縮にともない，これらの小ひびの形成が認められる。しかし，その挙動は，根系の有無により大きく異なっている。根系が土壌の収縮に及ぼす影響は，土壌の物理的な固定と水分吸収の二つの働きに起因する。通常，これらは同時に作用するため，機構的な区別が十分なされていない。本研究では，水稲栽培期間中の水田を乾燥させた後に土壌を採取し，それらの体積含水比および気相比と，含まれる根の密度との関係を解析した。その結果，根系は，水分の吸収と土壌の固定の両者を同時に作用させて乾燥時に土壌中に小ひびを誘起しているが，水分を吸収しなくとも，土壌中の細かいひびの発生を増大させる作用があることが明らかになった。

**キーワード** : 土壌の収縮，根密度，内部亀裂，土壌の補強，土壌水分の吸収

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