Analysis of the drying efficacy of some Vertisol management technologies using a simple model

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ABSTRACT

The drying efficacy of four technologies for managing the Vertisol of the Accra Plains of Ghana were evaluated with a simple empirical model of the form:

$$\theta\,(t) = a\,t^{-b}$$

where $\theta\,(t)$ is the moisture content to a depth of 15 cm ,at different times during the drying process, t is time, and the parameters a and b describe the initial moisture content and the rate of field-drying, respectively. The technologies evaluated were the cambered bed, the Ethiopian bed, the ridge, and the flat bed. The agricultural productivities of these technologies were also assessed by using maize as the test crop. Leaf area index, root mass, plant height, and grain yield per cob for maize were measured and used in the assessment. The parameter a was highest with the flat bed, followed by the Ethiopian bed, the ridge, and the cambered bed in decreasing order. The parameter b was the reverse of the trend obtained for the parameter a. The parameters a and b were used to explain the variations in growth, root development, and yield of maize on the various landform technologies. The results indicated that the parameter a was negatively and significantly correlated with plant height, root mass, leaf area index, and grain yield of maize. This confirms the assertion that the higher the initial moisture level in excess of the optimum requirement for plant growth, the lower the Vertisol can support the growth and yield of most crops. The study further showed that in the wet season, and for the Accra Plains Vertisol of Ghana, in particular, management technologies that gave faster rates of field-drying were more productive agriculturally.

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RÉSUMÉ

ASIEDU, E. K. & BONSU, M. : ***Analyse de l'efficacité de séchage de quelques technologies de gestion de vertisol utilisant un modèle simple.*** L' efficacité de séchage de quatre technologies pour la gestion de Vertisol de la Plaine d' Accra du Ghana était évaluée utilisant un modèle empirique simple de la forme: $q\,(t) = a\,t^{-b}$, où $q\,(t)$ est le contenu d'humidité à 15 cm de profondeur aux différents temps pendant le processus de séchage, t est le temps, et les paramètres a et b décrivent respectivement le contenu d' humidité initiale et la proportion de séchage au champ. Les technologies évaluées étaient : la couche cambrée, la couche éthiopienne, la crête et le plateau. Les productivités agricoles de ces technologies étaient également évaluées utilisant le maïs comme la culture d'essai. L' indice de surface foliaire, la masse de racine, la taille de plante, et le rendement de grain par épi pour le maïs étaient mésurés et utilisés dans l'évaluation. Le paramètre a était découvert d'être le plus élevé avec le plateau, suivi par la couche éthiopienne, la crête, et la couche cambrée dans l'ordre décroisant. Le paramètre b était l'inverse de la tendance obtenue pour le paramètre a. Les paramètres a et b étaient utilisés pour expliquer les variations en croissance, le développement de racine et le rendement de maïs sur les différents technologies de forme de terre. Les résultats indiquaient que le paramètre a était négativement et considérablement corrélé avec la taille de plante, la masse de racine, l'indice de surface foliaire et le rendement de grain de maïs. Ceci confirme l'assertion que le plus élevé que sera le niveau d' humidité initiale en excès de l'exigence optimum pour la croissance de plante, le plus faible sera le vertisol de soutenir la croissance et le rendement de la plupart de cultures. L'étude montrait en plus que pendant la saison humide et en particulier, pour le Vertisol de Plaines d' Accra du Ghana, les technologies de gestion qui donnaient des proportions plus rapides de séchage au champ étaient plus productives en agriculture.

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Introduction

Vertisols are reported to be the most widely dispersed soils in the world (Dudal, 1963). Even though they are potentially productive, they have remained under-utilized over the ages.

One factor that accounts for the low use of Vertisols for agricultural productivity worldwide is their peculiar moisture characteristics. According to Caughlan, McGarry & Smith (1987), surface water-logging is among the constraints to crop production on the Vertisol. Verma (1988) observed that on flat lands (slope less than 0.5 per cent), rain water causes problems of water-logging and water stagnation on Vertisols which become almost impervious with the addition of excess water. Even under severe drought conditions, Vertisols become water-logged after heavy rains, unless surface drainage is properly provided and maintained.

The amount of moisture contained in Vertisols determines such important factors as readily available moisture capacity (RAM), workability, trafficability, consistency, swelling and shrinking potential. The drying efficacy of the Vertisol is therefore of prime importance in managing the soil.

The results of various experiments have indicated that the key to improving productivity of Vertisols is the effective control of excess surface water (Abebe, 1982; Jutzi *et al.*, 1987). Therefore, drainage in Vertisols is a pre-requisite for realizing the full productive potential of the soils.

In Ghana, Vertisols can be found in the Accra Plains and the Interior Savanna Zone, and they occupy about 2.5 per cent of the total area of Ghana. Their coverage in the Accra Plains is estimated at 163,000 ha while in the Interior Savanna Zone, they cover some 19,000 ha (Adu & Stobbs, 1981).

In an attempt to improve the productivity of Vertisols in the Accra Plains of Ghana, the four management technologies assessed were the cambered bed, the Ethiopian bed, the flat bed, and the ridge. These technologies were evaluated by crop performance and yield (Dua-Yentumi, Owusu-Bennoah & Oteng, 1992) as well as physical properties (Asiedu, 1996). The results of the latter work confirmed what has been observed by many scientists that the drying efficacy of Vertisols is paramount in determining the soils' productivity. Analysis of the drying efficacy of any landform technology to be adopted on the Vertisol is, therefore, essential in predicting the efficiency of such technology.

The objective of this work is to use field-drying curves to analyse the drying efficacy of four Vertisol management technologies, using a simple empirical model. The description of the field-drying process in a simple mathematical relationship will facilitate the prediction of field moisture data that will be useful in irrigation practices and for managing the soils for increased agricultural productivity.

Materials and methods

Experimental site

The experiment was carried out at the University of Ghana Agricultural Research Station at Kpong, in the Eastern Region of Ghana where rainfall pattern is bimodal. The major rainy season of the area starts from March and lasts until mid-July, followed by a short dry spell that runs till the end of August. The minor rainy season starts from early September and ends in mid-November. There are about 71-80 rainy days in a year in the area, with a mean annual rainfall of 1,134.5 mm recorded over 30 years (Ghana Meteorological Service Annual Records: 1961-1990). Reference evapotranspiration (ETo) is in the order of 1500-1800 mm annually (Ghana Meteorological Services Annual Records: 1961-1990).

The soil of the experimental area is colluvial material derived from the weathering of garnetiferous hornblende gneiss (Brammer, 1955). It is classified as Eutric Vertisol (FAO) and Typic Calciustert (USDA). Locally, it is the tropical black clay and belongs to the Akuse series (Adu, 1985). The elevation of the study area is 18 m above sea level. The land is gently sloping with a general slope of less than 1.0 per cent. This, coupled with the high clay content (47.0 - 49.6 per cent clay) (Asiedu, 1996), subjects the land to poor drainage and flooding in the wet season. The type of clay contained in this soil is montmorillonite which has high shrinking and swelling potential and, therefore, influences the behaviour of the soil under different moisture conditions.

Field design of experiment

The randomised complete block design was used, with the four landform treatments replicated four times. The treatments were flat beds, Ethiopian beds, ridges, and cambered bed.

The four treatments, each covering an area of 9.6 m × 7.5 m, were replicated four times.

Land preparation

The field was slashed with a rotary slasher mounted on a tractor, ploughed and harrowed soon after the major rains. The landforms were then prepared as follows:

Flat beds. A polydisc plough with a one-way disc harrow of 9-12 discs was mounted on a 4-WD, 56-KW, 75-hp tractor and used for the preparation of the flat beds.

Ridges. A concave lister mouldboard ridger was mounted on the tractor and used to prepare the ridges. Twelve ridges, spaced 0.8 m apart, were prepared for each of the plots. Each ridge had a length of 7.4 m, a width of 0.8 m at the base, and a perpendicular height of about 0.30 m.

Cambered beds. A polydisc plough with a one-way disc harrow mounted on a 4-WD, 56-KW (75 hp) tractor was used to prepare the cambered beds. The cambered beds, each measuring 7.4 m long, 4.8 m in width and 0.35-0.40 m in height at the crest, were prepared.

Ethiopian beds. A tractor tool carrier with 560 mm scalloped disc was mounted on a 4-WD, 56-KW (75 hp) tractor and used to prepare the Ethiopian beds. The beds measured 1.6 m wide and 7.5 m long with a perpendicular height of about 0.3 m.

All the landforms had furrows of 0.8 m width, 0.3 m depth, and a lengthwise slope of less than 1.0 per cent.

Planting

The field was planted to maize (*Zea mays* var "Obatanpa") on 3rd September 1994, at a spacing of 0.8 m × 0.4 m. Two plants per hill were maintained, giving a planting density of 62,500 plants/ha.

Data collection

Soil moisture for field-drying studies. The gravimetric method of soil moisture determination was used (Gardner, 1965). The soil was sampled for moisture determinations 2 days after a heavy rainfall when it was close to field capacity, using the soil auger.

Four soil samples from each of the different landforms were thereafter taken daily at about the same time (08-09 h) at a constant depth of 0-15 cm and oven-dried at 105 °C for 24 h to determine the gravimetric moisture content. Soil moisture was determined daily as the soil progressively dried up, without any moisture addition to the soil by rainfall or irrigation, until after 6 days when it rained. The soil moisture determinations were then stopped, since the drying process was disrupted by the rain. The data were used in plotting field-drying curves for the landforms under investigation. These data were collected at the grain-filling stage of the crop; therefore, the changes in moisture data collected designated combined drainage and total evaporation.

Soil temperature. Soil temperature was measured at a depth of 10 cm for all the landforms with soil thermometers (Richards, Hagan & McCalla, 1952; Blanc, 1958). Precaution was taken to ensure that the thermometer bulbs were always in good thermal contact with the soil. Four replicate soil temperature readings were taken for each landform at about the same time each day (between 14-15 h GMT) for 16 consecutive days, and their daily mean values were determined.

Root development studies. Ten maize plants from each treatment plot were sampled randomly at maturity (95 days after planting). Their roots were carefully dug out with a ball of earth around them by using a chisel. The digging was done at a distance sufficient enough from the stem to ensure that there was no damage to the roots. Adhering soil was removed by carefully washing the root mass in a pool of water by standing the roots in a water bath for about 24 h, and then shaking the roots in the water. After all the adhering soil particles had been washed off the roots, the root system was separated from the stem by cutting with a knife. The roots were clean-washed and then air-dried for 2 days. The air-dried root samples were then weighed. The oven-dry mass of the roots was determined by weighing after drying to a constant weight in an oven at 60 °C.

Maize grain yield. The cobs on the plants sampled for root studies were harvested, dehusked, and weighed individually to determine the cob mass. The grains on the cobs were then shelled and weighed to determine the grain mass. The mean grain yield per cob (kg) was determined for each landform by dividing the total grain mass by the number of cobs from which the grains were shelled for each landform.

Leaf area index (LAI). Leaf area index was estimated for the maize plants just after tasseling when the plants were not expected to produce any more leaves. The procedure recommended by Sexana & Singh (1965) was used. Quadrants measuring 2 m × 2 m were demarcated randomly on each of the four landforms under experimentation. Leaf lengths and maximum widths of all plants within each quadrant were measured intact on the plant with the metre rule. Each leaf area was estimated by the following relationship:

$$\text{Leaf area for maize} = L \times B \times 0.75$$

(Sexana & Singh, 1965),

where L is the leaf length (m) and B is the maximum leaf width (m). The summation of all the leaf areas (i.e., total leaf area) in a quadrant was divided by the area of the quadrant to determine the LAI:

$$\text{LAI} = \frac{\text{Total leaf area per quadrant}}{\text{Ground area of quadrant}}$$

Results and discussion

Field drying of the Vertisols in relation to the various landforms

The field-drying curves. Fig. 1 shows the field drying curves for the various Vertisol landforms.

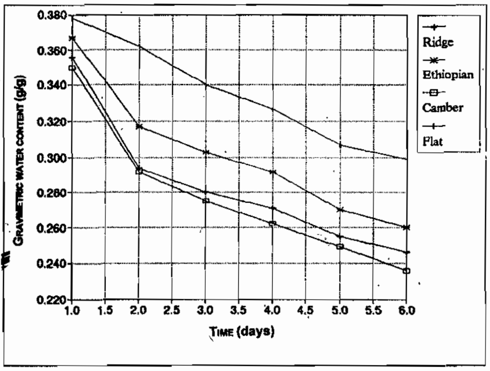

Fig. 1. Field-drying curves of the Vertisol landform.

The field-drying curves describe the gravimetric water content at various times during soil drying without water application.

It is assumed in this study that the drying of the soil could be described by the following empirical relation:

$$\theta\,(t) = a\,t^{-b}$$

where θ is the gravimetric water content at different times t, and a and b are parameters that relate to the drying efficacy of the soil. Then, by logarithmic transformation, the equation becomes:

$$\log \theta\ (t) = \log a - b \log t$$

Thus, it is expected that a plot of $\log \theta\ (t)$ against $\log t$ should give a straight line with a negative gradient equal to b and the intercept on the ordinate as $\log a$. Using the simple empirical model of equations mentioned above (derived by the authors) to represent the field-drying process, plots of $\log \theta$ against $\log t$ for the various landforms were determined, using data for 6 days of drying (Fig. 2). Plots of $\log \theta$ against $\log t$

were linear, as predicted by the model. Furthermore, the magnitude of the parameters *a* and *b* were determined by regression of *log θ* on *log t*. Table 1 shows the values of *a* and *b*. By considering the magnitudes of the parameter *b* in absolute terms, it was noted that the cambered bed had the highest value of *b*, followed by the ridge, the Ethiopian bed, and the flat bed in that order. However, the magnitudes of *b* for the cambered bed, the Ethiopian bed, and the ridge were not significantly different, but were different from that of the flat bed.

The field-drying process was influenced by the combined effect of drainage and evapotranspiration. The parameter *b* designates the rate of drying of the soil. Thus, the steeper the slope of the drying curve, the faster the drying rate. The variations in drying rates among the various landforms could be attributed to differential drainage and evapotranspirational effects. Differences in drainage among the various landforms could be ascribed to the extent of looseness and the height and volume of the heap of soil relative to the level ground. The parameter *b* indicated that drainage and evapotranspiration were fastest in the cambered bed, followed by the ridge, the Ethiopian bed and the flat bed, in that order, as similarly reported by Gama, Bagarama & Mowo (1992).

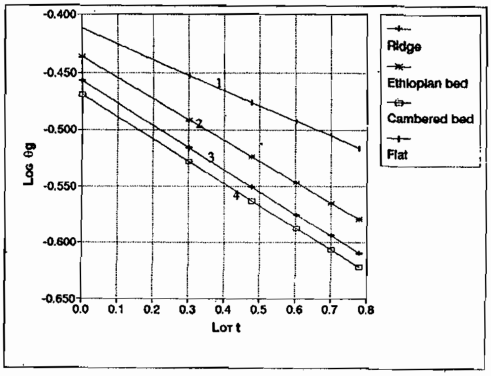

Fig. 2. *Log θ* versus *log t* regression curves for the various landforms.

Regression equations

1: $y = -41195 - 0.13412x$ ($R^2 = 0.943$)**
2: $y = -0.43575 - 0.18429x$ ($R^2 = 0.981$)**
3: $y = -0.45707 - 0.19606x$ ($R^2 = 0.976$)**
4: $y = -0.46895 - 0.19648x$ ($R^2 = 0.993$)**
** Significant ($P<0.01$)

TABLE 1

Regression on Parameters of Log θ (t) *Versus* Log t *(days) During Drying of the Vertisol Landforms*

Landform	*Log a*	*Anti-log of intercept (a)*	*Slope of log θ (t) versus log t (b)*	R^2
Flat bed	-0.4120	0.387	-0.1341	0.9423
Ethiopian bed	-0.4358	0.367	-0.1843	0.9803
Ridge	-0.0572	0.349	-0.1961	0.9763
Cambered bed	-0.4690	0.340	-0.1965	0.9992

The field-drying trend could be attributed to differential soil temperature effects (Fig. 3). Evaporational losses are, therefore, expected to be highest in the cambered bed, followed by the ridge, then the Ethiopian bed, and finally the flat bed, in accordance with the trend in the soil temperature values. This trend agreed with the absolute values for the parameter *b*.

The field-drying trend could also be attributed to transpiration, since the fields had maize growing on them. Differential rates of transpiration were expected on the different landforms due to differential root development, plant vigour, and leaf area indices that allowed differential plant water absorption and transpiration.

By taking the anti-log of *log a*, the real values of *a* were determined. Table 1 shows the values of *a* for the various landforms. The values of *a* depict the water content at the initial time of drying. It was observed that the *a* value decreased in the order: flat bed > Ethiopian bed > ridge > cambered bed. The value of *a* followed the reverse of *b* in trend for the various landforms.

Relating drying parameters a *and* b *of the various landforms with plant parameters*

Table 2 shows the various plant parameters

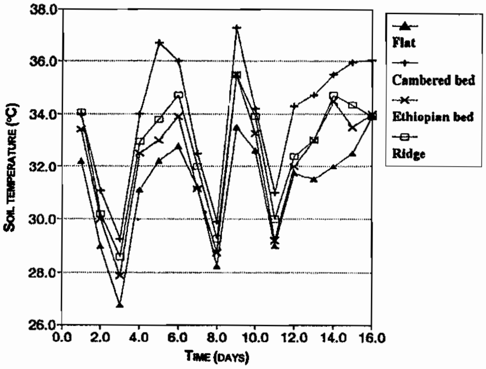

Fig. 3. Daily soil temperature variations in various landforms on the Vertisol at ARS, Kpong.

taken for the landforms while Table 3 shows the correlation coefficients between the field-drying parameter *a* and some plant parameters. The field-drying parameter *a* which signifies the initial soil moisture before field drying, was found to influence plant performance. Maize leaf area index, root mass, plant height, and grain yield per plant all decreased as the parameter *a* increased for all the landforms (Table 3). It was also observed that all the plant parameters measured were highest for the cambered bed which had the lowest *a* value but highest *b* value. The ridge followed the cambered bed, then the Ethiopian bed and the flat bed, in that decreasing order. Thus, it is not surprising that the flat bed which had the highest value of parameter *a* significantly recorded the lowest plant growth.

TABLE 2

Means for Leaf Area Index (LAI), Root Mass, Plant Height and Grain Yield per Cob

Landform	*Leaf area index (LAI)*	*Root mass (g)*	*Plant height (cm)*	*Grain yield per cob (g)*
Cambered bed	1.528^{a}	9.59^{a}	165.3^{a}	89.650^{a}
Ridge	1.286^{b}	8.41^{b}	153.4^{b}	71.832^{b}
Ethiopian bed	1.209^{b}	8.10^{b}	153.2^{b}	65.350^{b}
Flat bed	0.885^{c}	5.76^{c}	134.8^{c}	33.958^{c}

Means bearing the same letter in a column are not significantly different at $P=0.05$

These findings imply that, in the wet season, crop performance is better on the Vertisol with technologies that have more effective drainage. The higher the initial water content of the soil, the lower the degree of soil aeration, and the poorer the expected crop performance. The initial water content can influence both the timeliness of tillage operations and planting on the Vertisols. Tillage activities and planting can begin on the cambered bed earlier than all the other landforms as a result of comparatively low initial soil moisture conditions.

TABLE 3

Correlation Coefficients of Drying Parameter a with LAI, Mean Root Mass, Mean Plant Height and Mean Grain Yield per Plant for Maize

Correlation	*Correlation coefficient (r)*
a versus LAI	-0.972**
a versus mean root mass	-0.965*
a versus mean plant height	-0.944*
a versus mean grain yield per plant	-0.975**

* Significant ($P=0.05$)
** Highly significant ($P=0.01$)

The numerical values of the drying parameter *a* also suggested that for the technologies under investigation, plants grew better as the initial soil moisture level decreased progressively from 38.7 per cent on the flat bed through 36.6 per cent on the Ethiopian bed, and 34.9 per cent on the ridge to 34.0 per cent on the cambered bed. A similar trend relating landform to crop performance was observed by Mamo (1989). Since the trend in magnitude of the parameter *b* is the reverse of *a* invariably, all the plant parameters measured increased as the parameter *b* increased in magnitude (Tables 1 and 2).

Table 3 shows the correlation analysis of the drying parameter *a* with the various plant parameters. The results indicate that the parameter *a* is negatively and significantly correlated with plant height, root mass, leaf area index, and grain yield per plant. This confirms the assertion that the higher the initial moisture level in excess of the optimum requirement, the lower the Vertisol can support the growth and yield of most crops. This should be expected since moisture, in excess of the optimum level, reduces the air-filled porosity of the Vertisol, which in turn affects root development. Therefore, once root development is impaired, plant growth and yield are consequently suppressed.

As the removal of excess water through drainage improves the root-zone aeration of the soil, root development and plant growth and yield are enhanced, as far as there is sufficient available soil moisture in the soil to support plant growth.

Conclusion

It was possible to evaluate field drying of the Vertisol management technologies, using a simple empirical model of the form:

$$\theta(t) = a\,t^{-b}$$

where $\theta(t)$ is the moisture content at different times during the drying process, *t* is time, and *a* and *b* are parameters that relate to the drying efficacy of the soil.

The results showed that the cambered bed had the highest value of the parameter *b*, followed by the ridge, the Ethiopian bed, and the flat bed in that decreasing order. The parameter *b* signified the rate of field drying, and suggested that the cambered bed dried fastest while the flat bed took the longest time to dry.

There was a high positive correlation between maize growth and yield parameters and the parameter *b*. This suggested that in the wet season, the higher the rate of field drying of the Vertisol, the more suitable the soil is expected to be for the cultivation of most upland crops. Therefore, technologies that ensure a faster rate of field drying of the Vertisol are expected to be agriculturally superior.

The parameter *a* followed the order: flat bed > Ethiopian bed > ridge > cambered bed. The parameter *a* signified the initial moisture content of the soil and suggested that the cambered bed contained the least, and the flat bed, the highest amount of water at the beginning of the field-drying process.

The values of parameter *a* in relation to the plant parameters suggested that the more the moisture content in excess of the optimum level in the Vertisol, the poorer the agricultural suitability of the soil for cultivating upland crops.

Therefore, Vertisol management technologies which give high moisture retention in the wet season are probably the least desirable and *vice-versa*. The model derived by the authors in this work can, therefore, be used to predict the suitability of various management technologies for the Vertisol in the wet season based on their relative moisture retention characteristics.

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