Pertanika J. Trop. Agric. Sci. 37 (3): 321 - 330 (2014)

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Silt Pit Efficiency in Conserving Soil Water as Simulated by HYDRUS 2D Model

Mohsen Bohluli*, Christopher Teh Boon Sung, Ahmad Husni Mohd Hanif and Zaharah A. Rahman

Department of Land Management, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ABSTRACT

Silt pit is one of the recommended soil water conservation practices in oil palm plantations. It is commonly regarded that the larger and deeper the silt pit, the more effective the pit would be to conserve soil water. This hypothesis was tested in this paper, where the effectiveness of four silt pit dimensions on conserving soil water in the oil palm active rooting zone was simulated using the HYDRUS 2D model. These silt pits had different sizes and total wet wall-to-floor area ratio (W:F): H1 silt pit (1x1x1 m of width, length, and depth, respectively, and W:F ratio of 4.0), H2 (1.5x1x1 and W:F of 2.5), H3 (2x1x0.5 and W:F of 1.5) and H4 (2×1×2 and W:F of 1.5). Simulations showed that silt pits with larger W:F ratios could store water for longer periods and feed water to a farther horizontal distance within the soil compared to silt pits with smaller W:F ratios. H1 took the longest to dry out, whereby it took 14 to 19 hours longer to dry out compared to than H2, H3 and H4. H1 and H3 could feed water as far as 80 cm away from the pit more than H2 and H4 (60 and 50 cm, respectively). This is because silt pits with larger W:F ratios had larger horizontal water flow than the vertical water flow. Meanwhile, the depth of a silt pit should not be below the oil palm active rooting depth, which water would flow out of reach by the roots. This study is a preliminary work to a field experiment where simulations from this paper would be validated against measurements obtained in the field before recommending the use of silt pits and their size to be constructed in oil palm plantations.

Keywords: HYDRUS 2D, oil palm, silt pit, soil water conservation

ARTICLE INFO

Article history:
Received: 28 May 2014
Accepted: 19 June 2014

E-mail addresses:
bohluli.mohsen@gmail.com (Mohsen Bohluli),
cbsteh@yahoo.com (Christopher Teh Boon Sung),
husni@upm.edu.my (Ahmad Husni Mohd Hanif),
zaharah47@gmail.com (Zaharah A. Rahman)
* Corresponding author

INTRODUCTION

Further expansion of new oil palm plantations in Malaysia is currently limited to marginal lands which include steep lands. Accelerated

ISSN: 1511-3701

soil erosion on steep slopes causes soil fertility reduction, fresh and ground water pollution and other environmental problems. Hartemink (2006) reported that the erosion under natural forests is less than 1 Mg ha^{-1} yr^{-1}, while the maximum soil erosion under oil palm plantations is 78 and 28 Mg ha^{-1} yr^{-1} for Oxisols and Ultisols, respectively. Chew *et al*. (1999) also determined 7 to 21 Mg ha^{-1} yr^{-1} of soil erosion in matured oil palm plantations. Soil erosion reduces oil palm production not only by decreasing soil fertility and organic matter but also by reducing soil water infiltration, soil water content and soil water holding capacity that would consequently cause lesser available soil water content.

Although Malaysia experiences high total annual rainfall (2000-3000 mm), studies have shown that proper water management could further increase oil palm yield. Annual oil palm production, for example, could increase by a mean of 73% when all of the oil palm's daily water demands were fulfilled through irrigation (Foong, 1999). Roslan (2006) observed that irrigation could increase fresh fruit bunches yield of oil palm by 10% compared with rain-fed oil palms in the first harvesting year. Gawankar *et al*. (2003) showed that water stress reduced leaf production by 30 and 12.5% at the early and later growth periods, respectively, as well as a decrease by 91% in the number of fresh fruit bunches due to the reduction of female inflorescences by 86%.

Hartemink (2003) has shown that soil erosion in oil palm plantations is highly related to slope steepness and soil water management practices. Silt pit is one of the recommended soil-water conservation methods in Malaysia (Teh *et al*., 2011). Goh *et al*. (1994) mentioned that maximum oil palm yield production in Malaysia could be increased by yield intensification through land management practices such as silt pits. Silt pits are close-ended trenches dug between oil palm plantation rows, particularly on steep slopes, to break the slope length to smaller catchments, collect run-off and sediments (which contain nutrients) and to redistribute water and nutrients into the oil palm root zone area after rainfall. Silt pits function by reducing soil erosion, controlling run-off and sedimentation, increasing oil palm yield through supplying more water, especially during dry weather, as well as protecting and increasing soil fertility through reduction of nutrient loss and redistribution of eroded nutrients back into the soil. Although silt pits have been practiced for several decades, there have been only a few studies done to determine the effectiveness of silt pits, particularly in high rainfall areas like in Malaysia.

One of the few studies was by Soon and Hoong (2001) who had recorded the highest runoff for plots with pruned fronds stacked down the slope (30.83%), followed by plots with contour stacked fronds (17.88%), and plots with the least runoff were those with contour stacked fronds + silt pit (10.68%). Hidayat and Sutarta (2008) reported that bund terraces were effective to reduce overland flow and soil erosion by 50.8% and 67.5%, respectively. Compared with the control, however, silt pit reduced overland flow and soil erosion by 94.9% and 98.1%, respectively. Murtilaksono *et al*. (2008) observed that the number of fronds, number of bunches, average bunch weight and fresh fruit bunches (FFB) were significantly increased by silt pit. Nonetheless, bund terrace increased FFB (25.2 t ha^{-1}) more than silt pit (23.6 t ha^{-1}) and both these methods yielded more than that of the control (20.8 t ha^{-1}). Although bench terraces were able to improve oil palm production more than silt pits, silt pits were more effective in reducing erosion and increasing soil water conservation compared with bench terraces. For example, the combination of bund terraces and silt with mulches reduced overland flow to 26.17 and 1.99 mm, respectively, and total soil erosion to 238.68 and 13.90 kg ha^{-1}, respectively, compared with the control (60.66 mm overland flow and 729.28 kg ha^{-1} total soil erosion) (Hidayat & Sutarta, 2008). Murtilaksono *et al*. (2011) also found that bench terraces and silt pits increased soil water contents from 133.80 to 141.25 mm and 165.11 to 200.98 mm, respectively, compared to the control.

Silt pits have been used in the "Ngoro" system in Tanzania for several hundred years. This indigenous soil and water conservation method enables plantation to be done in areas with 10 to 60% slopes (Kayombo *et al*., 1999). Mally *et al*. (2004) studied the effects of different pit sizes in the Ngoro system for maize cultivation. They reported that application of pits reduced soil erosion significantly and that the larger the pit, the higher the yield of maize would be because of the higher water infiltration and soil water content.

It is commonly believed that the larger and deeper the silt pit, the higher the amount of stored water would be returned to the soil. A silt pit must be able to capture maximum run-off and also to redistribute the collected water into the oil palm active root zone to avoid it from being lost through deep percolation. The water must also be stored for long periods of time for it to be used by oil palm during the dry periods. Hence, the main question in this study was: how does the size of silt pit (dimensions) affect the effectiveness of pits to conserve water into oil palm root zone? In other words, is it better to have larger and deeper silt pit? The objective of this study was to simulate the effectiveness of various silt pit dimensions in conserving soil water content by using the HYDRUS 2D model. This simulation is a preliminary work to a field experiment in which the effectiveness of silt pit dimensions, as reported in this paper, would be compared with one another in field conditions.

The HYDRUS 2D/3D model (Simunek *et al*., 2006; Sejna & Simunek, 2007) is a software package used for the simulation of two- and three-dimensional movement of water (as well as heat and multiple solutes) in a variably saturated media. The HYDRUS model assumes the following: an insignificant role of air phase in liquid flow process, zero pressure head along a drain located in saturated zone, water leaves the saturated zone by overland flow, and the mass transfer rate is proportional to the differences in water contents rather than pressure head.

The most important input parameters required by HYDRUS are the water flow parameters including residual water content (Q_r), saturated water content (Q_s), saturated hydraulic conductivity (K_s), empirical coefficients of the hydraulic functions (α and n) and pore-connectivity (I), which affect total soil water capacity and soil water movement (Brooks & Corey, 1964). Water flow parameters can be estimated from measured soil water retention curve, measured soil texture or soil textural classes, which are represented as defaults in the soil hydraulic catalogue of HYDRUS.

There are almost one thousand peer-reviewed journal references where the HYDRUS model has been used. For example, Tadaomi *et al*. (2012) simulated the distribution of water content and water fluxes in a water harvesting system (ditches filled with sand) by using HYDRUS 2D. Comparisons between simulated and measured results showed an acceptable agreement. The validity of HYDRUS 2D in terms of water distribution and infiltration in terraced slopes had been tested by Haishen *et al*. (2008), who reported a good agreement between simulated and measured data. Meanwhile, Raoof and Pilpayeh (2011) examined the accuracy of numerical inversion solution of HYDRUS 2D in simulating soil wetting profile (1m depth) under saturated and unsaturated conditions in different degrees of slope steepness. They reported an estimation average error of 3.22% and root mean square error of 0.032 between measured and simulated data. Zhang *et al*. (2013) investigated the distribution of infiltrated water in the cross section of furrow irrigation system through laboratory experiments and HYDRUS 2D model. They remarked that the observed and simulated data were highly in agreement based on the mean square error and coefficient of determination (R^2).

MATERIALS AND METHODS

Four treatments of silt pit dimensions were selected and shown in Table 1.

The data on soil hydraulic and physical properties were collected from Tuan Mee oil palm plantation (03° 16' N and 101° 28' E) at Sg. Buloh in Malaysia. The field site

TABLE 1
Silt pit sizes used in the simulations

Treatment	Silt pit size (m) Width × Length × Depth	Volume (m^3)	Opening or floor area (m^2)	Wet wall to floor area ratio (W:F)	Head of water* (m)
H_1	1.0×1.0×1.0	1.0	1.0	4.0	1.00
H_2	1.5×1.0×1.0	1.5	1.5	2.5	0.75
H_3	2.0×1.0×0.5	1.0	2.0	1.5	0.50
H_4	2.0×1.0×1.0	2.0	2.0	1.5	0.50

* Indicates the height of stored water from the floor of silt pit. A fixed volume of $1m^3$ of water was placed in all silt pits at the beginning of simulation.

has a slope steepness of 11°. The soil of this area is classified as Bungor Series (Typic Paleudult), which comprises low grade schists or in-durated shales. The mean total rainfall in Tuan Mee estate is 2440 mm, with an average of 160 mm monthly rain. The data used in the model were measured from the field: bulk density (1.35 Mg m^{-3}, core ring method, Blake & Hartage, 1986); sandy clay loam texture (USDA) with 24.92, 7.34 and 67.74 % clay, silt and sand, respectively; and the soil hydraulic properties (pressure plate and membrane technique. Richards (1974) were: permanent wilting point (0.13 m^3 m^{-3}), saturated point (0.44 m^3 m^{-3}), parameter α and n in the soil water retention function (2.00 cm^{-1} and 1.30, respectively), saturated hydraulic conductivity (0.02 m day^{-1}) and tortuosity parameter in the conductivity function (0.50).

The HYDRUS model numerically solves Richards' equation for water flow:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \quad [1]$$

where θ is the volumetric water content (L^3L^{-3}), h is the pressure head (L), S is the sink term (T^{-1}), x_i (i = 1, 2) is the spatial coordinates (L), t is the time (T), $K\frac{A}{ij}$ is the components of dimensionless anisotropy tensor and K is the unsaturated hydraulic conductivity (LT^{-1}).

Van Genochten (1980) function was used to characterize the shape of the soil water retention curve:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha|h|)^n]^{1-1/n}} \quad [2]$$

where θ(h) is the water content (L^3L^{-3}), $|h|$ is the pressure (L^{-1} or cm of water), θ_s is the saturated water content (L^3L^{-3}) and θ_r is the residual water content (L^3L^{-3}) taken to be the permanent wilting point in this study. Note that θ_s, θ_r, α and n are the four independent parameters that must be estimated from the measured soil water retention data. Meanwhile, α can be determined by solving the following:

$$\alpha = \frac{1}{h}\left(\Theta^{-1/m} - 1\right)^{1/n} \quad [3]$$

where Θ is the dimensionless normalized volumetric soil water content and m is given by:

$$m = 1 - 1/n \quad [4]$$

The following empirical formula was used to estimate m:

$$m = \begin{cases} 1 - \exp\left(-0.8\, S_p\right) \\ 1 - \frac{0.5755}{S_p} + \frac{0.1}{S_{p2}} + \frac{0.025}{S_{p3}} \end{cases}$$

$$\begin{matrix} (0 < S_p \leq 1) \\ (S_p > 1) \end{matrix} \quad [5]$$

where S_p is the slope of the soil water retention curve at a point halfway between θ_r and θ_s.

The soil geometrical and environmental conditions were set as constant across all silt pit treatments (dimensions). The topography was flat. Simulations assumed no evaporation and no plant water uptake and free drainage was further assumed in order to make the simulation simple.

A 50-cm soil depth was selected for the determination of soil water content because oil palm has a shallow active root system within the first 50 cm soil depth (Gray & Hew, 1968).

RESULTS AND DISCUSSION

Simulations showed that the smaller the silt pit floor area (or opening area), the longer it took for the pits to dry out (see Fig.1). In particular, H1, H2, H3 and H4 dried out in 72, 57.6, 52.8 and 52.8 hours, respectively. The simulations also showed that a larger horizontal distance (80 cm) of wetted front for H1 and H3, compared with 60 and 50 cm for H2 and H4, respectively (Fig.2). This means H1 and H3 could feed water horizontally farther into the top soil than H2 and H4.

Water can infiltrate vertically and laterally into a soil (Lal & Shukla, 2004). There would be a larger horizontal movement of water for silt pits with larger total wet wall-to-floor area (W:F) ratio. The narrow opening area of silt pits (H1 and H2) have larger W:F ratios (4 and 3.3, respectively) than H3 and H4 (1.5 for both). When a pit has a larger W:F ratio, the height of stored water in the silt pit would be nearer to the soil surface. Therefore, a larger wall area would be wetted, and this in turn would lead to a larger total water flux through the walls and smaller total flux through the floor compared with a silt pit with smaller W:F. Meanwhile, Sawhney and Parlange (1974) reported that the vertical infiltration is about twice as fast as horizontal infiltration. Therefore, the horizontal water infiltration is always slower than the vertical water infiltration into the soil. This is because vertical soil water movement is driven by both gravity and water potential differences compared with horizontal water movement which is driven only by the water potential

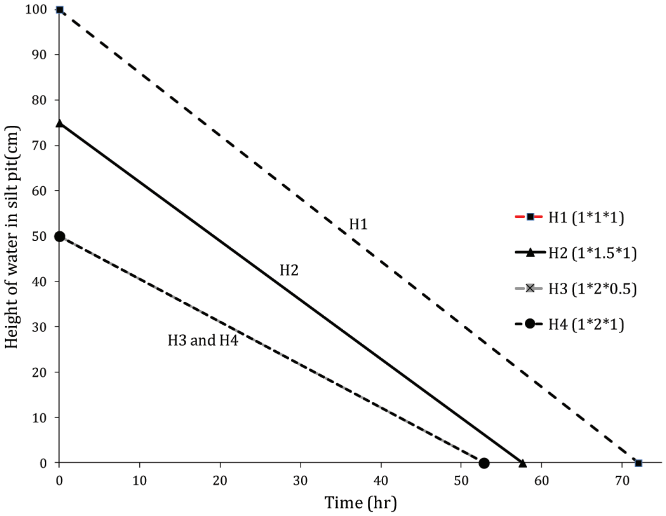

Fig.1: Temporal changes to the height of stored water from the floor of silt pit (Note: lines for H3 and H4 overlap each other)

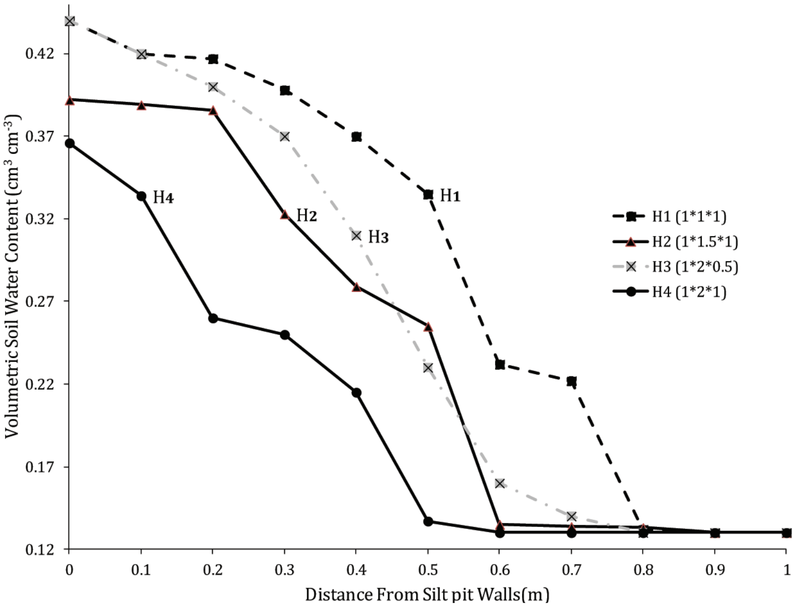

Fig.2: Volumetric soil water content at various horizontal distances from the silt pit walls. Soil water content at 0.50 m soil depth and at 72 hours.

gradient. Hence, silt pits with larger floor area lose water more through vertical than horizontal infiltration.

There is a slowing effect of horizontal infiltration on vertical infiltration (Talsma, 1969; Talsma & Parlange, 1972). In other words, an increasing horizontal infiltration causes a decreasing vertical infiltration. Slowing effect is another reason why silt pits with larger W:F ratios could release water slower (hence, store water longer). When larger wall areas in H1 become in contact with water, the quantity of horizontal infiltration will increase. This will then reduce the vertical infiltration.

Fig.3 displays a relationship between total water flux from walls and W:F values. When W:F ratio increases, the proportion of total horizontal water flux to total vertical flux increases. There is an inverse relationship between vertical flux and W:F. Therefore, H3 and H4 with the same W:F had similar horizontal and vertical total flux. The similar performance of H3 and H1 in terms of the wetted front distance (80 cm for both; Fig 2) was because both these pits had equal height of water inside the pit (50 cm) at 50 cm soil depth where the infiltration water was measured.

Increasing the W:F ratio resulted in increasingly more water flux out of the silt pit through its walls than through its floor. This is an important implication because the oil palm roots are located around the walls and not below the floor of the silt pit. Therefore, a silt pit with a large W:F ratio is able to redistribute the stored water to the surrounding root zone and avoid it from being lost through percolation via the silt pit floor and away from the root zone. This

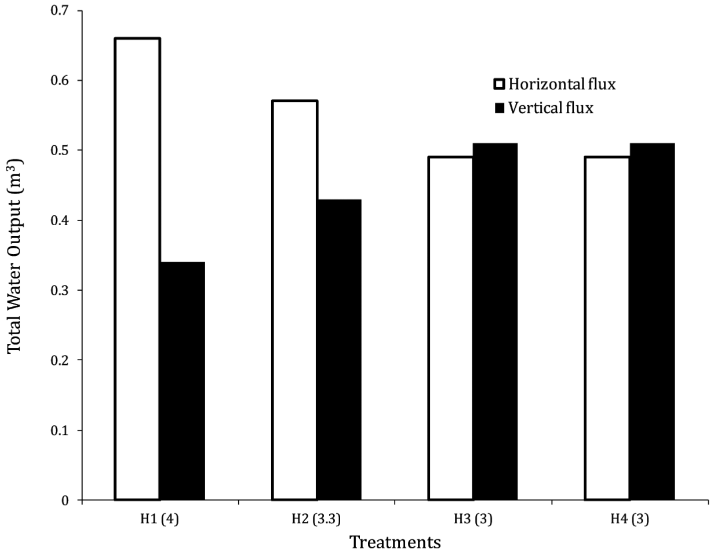

Fig.3: The amount of water output from the walls and floors of the silt pit treatments. Values in parentheses indicate total wall-to-floor area ratio (W:F) for the silt pit dimension. Width, length and depth for H1, H2, H3 and H4 are 1×1×1, 1.5×1×1, 2×1×0.5 and 2×1×1 m, respectively).

also means that the floor depth of a silt pit cannot be lower than the depth of the active oil palm roots, which will cause water loss to be particularly large for silt pits with very small W:F ratios.

As stated previously, water evaporation was not considered in this simulation. It was however expected that evaporation from a larger opening area would be higher from that of a smaller opening area. Therefore, water loss via evaporation would be more in a silt pit with a bigger opening area than that from a silt pit with smaller opening area. The opening area of H4 is twice of H1, which also means evaporation from H4 is double of that from H1. So, if evaporation was to be included in the simulations, H3 and H4 would dry out even quicker (see Fig.1) and have a smaller wetting front distance (Fig.2) than that reported here.

CONCLUSION

The simulations carried out in this study have shown that the water conservation ability of silt pits is dependent upon their W:F ratios. The larger the W:F ratio, the longer the silt pits could store water and the farther the water could be fed back to the surrounding soil. For the same volume of water, silt pits with a larger W:F ratio would have higher water head and are more horizontal than the vertical movement of water out of the silt pit. This made silt pit, H1 (1x1x1), to store the water the longest and had the farthest horizontal wetting distance than the other silt pit sizes (H2, H3 and H4). Hence, H1 was the best silt pit dimension to conserve soil water. The depth of the silt pit floor could not be lower than oil palm active rooting depth.

The next step of this study would be to carry out a field experiment using the four silt pit dimensions so as to determine the validity of the simulation carried out in this earlier work. Hence, the researchers hope to be able to recommend not only using silt pits as a soil water conservation method in oil palm plantations, but also the silt pit sizes to be constructed.

REFERENCES

Blake, G. R., & Hartge, K. H. (1986). Bulk Density. In A. Klute (Ed.) Methods of Soil Analysis: Part I. *Physical and Mineralogical Methods.* 2nd Edh. ASA-SSSA.

Brooks, R. H., & Corey, A. T. (1964). Hydraulic properties of porous media. *Hydrol.* (Paper No. 3). Colorado State Univ., Fort Collins CO.

Chew, P. S., Kee, K. K., & Goh, K. J. (1999). Cultural practices and their impact. Oil Palm and the Environment, Malaysian Perspective. In G. Singh, L.K. Huan, T. Leng, & D. L., Kow. (Eds.), *Malaysian Oil Palm Growers Council*. Kuala Lumpur.

Foong, S. F. (1999). Impact of Moisture on Potential Evapotranspiration, Growth and Yield of Oil Palm. *Proc. Of the 1999 international Palm Oil Congress Emerging Technologies and Opportunities in the Next Millennium* (pp. 64-86). PORIM, Bangi.

Gawankar, M. S., Devmore, J. P., Jamadangi, B. M., Sagvekar, V. V., & Khan, H. H. (2003). Effect of Water Stress on Growth and Yield of Tenera Oil Palm. *Journal of Applied Horticulture, 5*(1), 39-40.

Goh, K. J., Chew, P. S., Teo, C. B., & Chee, K. H. (1994). Maximising and maintaining oil palm yields on commercial scale in Malaysia. *International Planters Conference on Management for Enhanced Profitability in Plantations, Kuala Lumpur*, pp. 121-141.

Gray, B. S., & Hew, C. K. (1968). Cover crop experiments in oil palms on the West Coast of Malaysia. In P. D. Turner (Ed.), *Oil palm developments in Malaysia.* Inc. Soc. Planters, Kuala Lumpur.

Haishen L., Yonghua Z., Todd H. S., & Zhongbo Y. (2008). Comparison of Measured and Simulated Water Storage in Dryland Terraces of Loess Plateau, China. *Agricultural Water Management, 96,* 299-306.

Hartemink, A. E. (2003). *Soil Fertility Decline in the Tropics with Case Studies on Plantations*. Wallingford: ISRIC-CABI Publishing.

Hartemink, A. E. (2006). Soil Erosion: Perennial Crop Plantations. ISRIC. *Encycolopedia of Soil Science*.

Hidayat, Y., & Sutarta, E. S. (2008). Eefktivitas as Teras Gulud dan Rorak dalam Mengendalikan Aliran Permukaan dan Erosi pada Perkebunan Kelapa Sawit di Unit Usaha Rejosari, PT. Perkebunan Nusantara VII, Lampung. *Study Program Science of Land*. Faculty of Agriculture. Bogor Agricultural University.

Kayombo J., Ellis-Jones, & Martin H. L. (1999). Indigenous Conservation Tillage System in East Africa with an Example of Their Evaluation from South West Tanzania. In P.G. Kaumbutho and T.E. Simalenga (Eds.), conservation tillage with animal traction. *A Resource Book of the Animal Traction Network for Eastern and Southern Africa* (ATNESA).

Lal, R., & Shukla M. K. (2004). Principles of Soil Physics. *Books in Soils, Plants, and the Environment*. The Ohio State University Columbus. Marcel Dekker, Inc. New York, Basel.

Malley Z. J. U., Kayombo B., Willcocks T. J., & Mtakwa P. W. (2004). Ngoro: an Indigenous, Sustainable and Profitable Soil, Water and Nutrient Conservation System in Tanzania for Sloping Land. *Elsevier. Soil and Tillage Research 77*, 47-58.

Murtilaksono, K., Darmosarkoro, W., Sutarta, E. S., Siregar, H. H., & Hidayat, Y. (2008). Effort in Increasing of Oil Palm Production through Application of Soil and Water Conservation Measures. *Developing Tomorrow's Leaders in Agriculture and Rural Development: Responding to the Challenges of Globalization.* Posters.

Murtilaksono, K., Darmosarkoro, W., Sutarta, E.S., Siregar, H. H., Hidayat Y., & Yusuf, M. A. (2011). Feasibility of soil and water conservation techniques on oil palm plantation. *Journal of Agriculture Science, 33*, 63-69.

Raoof, M., & Pilpayeh, A. (2011). Estimating Unsaturated Soil Hydraulic in Sloping Lands by Numerical Inversion. *Journal Food, Agriculture and Environment, 9*(3&4), 1067-1070.

Richards, L. A. (1974). Pressure – Membrane Apparatus – Construction and Use. *Agri. Eng. 28*, 451-454.

Roslan, M. N. (2006). Effects of Water Stress on the Physiological Processes and Water Use Efficiency in Oil Palm. *Master Thesis, University Putra Malaysia.*

Sawhney, B. L., & Parlange J. Y. (1974). Two-Dimensional Water Infiltration from a Trench in Unsaturated Soils. *Soil Science Society of American Journal, 38*(6), 867-871.

Sejna, M., & Simunek, J. (2007). HYDRUS (2D/3D): Graphical User Interface for the HYDRUS Software Package Simulating Two- and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. *Published online at www.-pc-progress.cz, PC-Progress, Prague, Czech Republic.*

Simunek, J., Van Genuchten, M. T., & Sejna, M. (2006). The HYDRUS Software Package for Simulating Two- and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. *Technical Manual, Version 1.0, PC Progress, Prague, Czech Republic,* pp. 241.

Soon, B. B. F., & Hoong, H. W. (2001). Agronomic Practices to Alleviate Soil and Surface Runoff Losses in an Oil Palm Estate. *Malaysia Journal of Soil Science, 6*(Special Ed.), 53-64.

Tadaomi, S., Hiroshi, Y., Haryuki, F., Koji, I., & Yukuo, A.B.E. (2012). Numerical Calculation of Soil Water Movement in a Water Harvesting System with Sand Ditches Using HYDRUS 2D. *Journal of Arid Land Studies, 22*(1)*,* 215-218.

Talsam, T. (1969). In Situ Measurement of Sorptivity. *Aust J. Soil Res., 7,* 269-276.

Talsma, T., & Parlange, J.Y. (1972). One-Dimensional Infiltration. *Aust J. Soil Res., 10*, 143-150.

Teh, C. B. S., Goh, K. J., Law, C. C., & Seah, T. S. (2011). Short-term Changes in the Soil Physical and Chemical Properties due to Different Soil and Water Conservation Practices in a Sloping Land Oil Palm Estate. *Pertanika J. Trop. Agric. Sci., 34*(1), 41-62.

Van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *SSSA J. 44*(5), 892-898.

Zhang, Y., Wu, P., Zhao, X., & Wang, Z. (2013). Simulation of Soil Water Dynamics for Uncropped Ridges and Furrows under Irrigation Conditions. *Canadian Journal of Soil Science, 93*(1), 85-98.