

Communication

Title: Soil Water and high-quality development in water-limited regions

Zhongsheng Guo^{*1,2}, Yaolin Li², Ting Ning², Wenwen Zhang², Zhensheng Yan², Songwei Wang¹, DanDan Chen²

¹ Institute of Soil and Water Conservation, Northwestern A & F University, Yangling, China; zhongsheng-guo@sohu.com

² Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, China; guozs@ms.iswc.ac.cn

* Correspondence: zhongshengguo@sohu.com; Tel.: +862987012411; Fax. +86-29-8701-2210

Abstract: The goods and services produced by forest and vegetation ecology system is the power by which human society can be promoted fast in high-quality and sustainable way. With the increase of population and economic development in water-limited regions, there is an increasing demand for the quantity and variety of forest vegetation ecosystem products and services. To meet the demands of this situation, most of the original forest has changed into farmland, non-native forest and grass land. As a result, water-plant relationship changed from equilibrium to non-equilibrium, which led to soil drought, soil degradation and vegetation decline in dry years or waste of soil water in rainy years in most of water-limited regions. In order to solve the questions and realize the sustainable utilization of soil water resources and the high quality and sustainable development of social economy, it is necessary to apply the utilization limit theory of soil water resources by plants and the theory of soil water carrying capacity for vegetation to adjust the relationship between plant growth and soil moisture to obtain the maximum yield and benefit of vegetation and serve high-quality and sustainable development.

Keywords: goods and services, water-limited area; plant-water relationship; Soil water resource use limit by plants; Soil Water Carrying Capacity for Vegetation

1. Introduction

Water is a precious natural resource and Water covered 71% of the earth's land. Terrestrial water resources can be classified into surface water, underground water and soil water resources.

The goods or the products that people need, such as food, fiber and fuel wood and services, such as improving environment and soil and water conservation produced by plant ecology system is the power by which Human society can be promoted fast in high quality and sustainable way.

Terrestrial Plants usually absorb water by their roots, and other kinds of water resources must be translated into soil water resources and then absorbed by plants in water-limited regions. The soil water is the most important factor influencing plant growth in water-limited regions because underground water is deep and soil water mainly from precipitation without irrigation in some of the water-limited regions, such as Chinese loess plateau.

Terrestrial plant growth and soil water environment has been interacted. Along with plant growth, the plant-water environment in soil root zone plant grows have changed. The plant-water environment of plant growth was divided into water sufficient area where soil water can meet the need of plant growth and soil water insufficient area or water-limited area where water cannot meet the need of plant growth.

Most of the goods and services that people in the world enjoy are produced by forest and vegetation. To meet people's needs, most of old forest changed into non-native vegetation and changed the relationship between plant growth and soil moisture, which changed soil water and hydrology, and leading to soil dry, soil degradation and vegetation decline in dry years or waste soil water resources in rainy yeas. For example, along with

plant growth, soil drought occurred, resulting in soil degradation and vegetation decline in most areas of the region [1],[2],[3],[4] because the soil water supply mainly from precipitation [5],[6] and cannot meet the water needs of plants in dry year or wastes because the soil water supply from precipitation surpasses the water needs of plants in a rainy year Chinese loess plateau.

As a consequence, vegetation decline and eventually desertification in the artificial perennial grassland and woodland areas of the Loess Plateau [2],[3],[4] or soil water resources wastes in rain years. This, in turn, affects soil quality, non-native vegetation growth and its ecological benefits. This is not desirable for the sustainable use of soil water resources and high quality and sustainable development of forest and vegetation. To keep healthy growth of non-native vegetation and get its maximum produce and ecological benefits, water-plant relationship must be regulated by reducing plant density or lop a fruit tree in order to increase soil moisture supply, reduce evapotranspiration and maintain soil moisture balance and the stability of artificial vegetation ecosystem, to prevent soil drying and soil degradation or soil water waste. The rationale for regulation water-plant relation is that theory of Soil water resource use limit by plants and the theory of Soil Water Carrying Capacity for Vegetation. The purpose of the paper is to introduce the theories of Soil water resource use limit by plants and the theory of Soil Water Carrying Capacity for Vegetation.

Soil water resources

To understand the theory of Soil water resource use limit by plants and the theory of Soil Water Carrying Capacity for Vegetation, first we have to master the soil water resources because soil water resource is the basis of understanding the theory of soil water resource use limit by plants and the theory of Soil Water Carrying Capacity for Vegetation.

The concept of Soil Water Resources first put forward by Budagovski in 1985 [7] after the concept of overall soil moistening proposed by Lvovich in 1980 [8]. Soil water resources are the sum of water in the soil body, which are renewable water resources and components of water resources. There are generalized soil water resources and narrow sense soil water resources. Generalized soil water resources can be defined as the water stored in the soil from the surface soil to the water table, commonly used in geology or architecture, and narrow soil water resources is the water stored in the root zone, commonly used in forestry, grassland and agriculture. In addition, there are dynamic soil water resources, which are the antecedent soil water resources plus the soil water supply from precipitation in the growing season for deciduous plants, or over a year for evergreen plants. Soil Water Resources change with rainfall, soil evaporation, plant transpiration and soil water moving in the soil in most of the water-limited regions because under water is deep and without irrigation[9]. Rainfall decided soil water supply and soil water infiltration depth and soil water resource and hydrology [5].

Root vertical distribution

Root lives in soil root zone and is the principal supporting and water-absorbing organ of terrestrial life plant to suck soil water even though stoma in a leaf and a stem can suck a little water when air humidity is high, such as raining.

Root vertical distribution is an important index to estimate soil water deficit criteria because plant absorbs soil water in the root zone. Soil water resources are good indicator to express the effect of soil moisture on plant growth because plant roots are vertically distributed in soil and at the same time suck soil water in certain soil body. Sometime the root vertical distribution depth is more than tree height, see photo 1. The plant growth and root vertically distribution of Robinia (*Robinia pseudoacacia* L.) forest in the semi-arid loss hilly region (Guyuan, China).

Soil water resource use limit by plants (SWRULP)

Before understanding soil water resources resource use limit by plants, we have to put forward a suitable index to express plant water deficit. Soil water resources is the water storage in a given soil depth. Plant root cannot suck soil water unlimitedly in water-limited regions. There is the soil water limit plant use soil water. There are some soil water deficit indices, such as crop water index [10], soil water deficit index, evapotranspiration deficit index, plant moisture deficit index [11] to express soil water limit. Because most of the drought indices are based on meteorological variables [12] or on a moisture balance equation, they do not indicate water deficit accumulation or soil water storage (soil water resource) in root zone [13], they can express soil water deficit in a given soil body. But they cannot act as a suitable index for distinguishing severe drying of soil in the soil root zone of the water-limited regions because soil drought is a nature phenomenon, and a water deficit accumulation or a decrease in soil water storage in the root zone soil plant root distribute.

The amount of soil water resources changes with weather condition, plant growth and soil water movement in the soil. In order to achieve sustainable use of soil water resources, there should be a sustainable use indicator of soil water resources, that is to say that sustainable use indicator of soil water resources can express the suitable degree plant use soil water resources and it will easily be recovered. The limit is the soil water resources use limit by plants (SWRULP) [14]. The SWRULP can be defined as the soil water resources in the MID when the soil water content within the MID equals the wilting coefficient of an indicator plant [6] [14] [15]. Because the soil water content changes with soil water suction at different soil depth and the variation of soil water content with soil water suction accords with the Gardner equation, so we can use the Gardner equation to fit soil water content and soil water suction data and establish the soil water characteristics curve and then estimate the wilting coefficient at different soil depth [5] [16].

Soil Sampling

Before estimate soil water suction at different soil depth, we have to take undisturbed soil sample and measure the soil water suction of undisturbed soil where plant live and wilting. Generally, the sampling pits in soil profile was dug in the experimental site for investigating soil profile and sampling purposes, whose dimensions were $1\text{m}^2 \times 4\text{m}$ depth. The undisturbed soil samples were collected for 3 times at different soil depth with cutting rings (a 5 cm in high, 5 cm in inner diameter and 100 cm³ in cubage). Soil water contents at different soil suctions were measured by centrifuge method, generally using a HITACHI centrifuge, made by Instrument Co. Japan, or Pressure Chamber method made in USA.

Because Gardner empirical formula can better describe the relationship between soil water content W and soil water suction S , the wilting coefficient can be estimated by the Gardner empirical formula $W = a \cdot S - b$ [16].

Generally, the wilting coefficient is assumed to be the soil water content when the soil water suction is 1.5 mPa because soil water potential at wilting ranged from -1.0×10^5 to -2.0×10^5 mPa with an average of approximately -1.5×10^5 mPa (15 bar) [17]. For example, the change of soil water content with soil water suction at different soil depth in caragana (*Caragana korshenskii*) shrubland of semiarid loess hilly region, see Figure 1, and wilting coefficient varies with soil depth, see table 1. The wilting coefficient varies with soil depth, see the Figure 1 and Table 1.

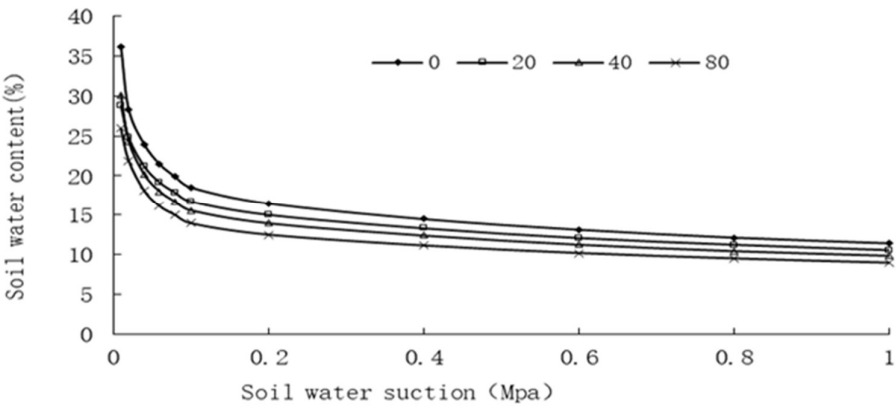


Figure 1. The changes of soil water content with soil water suction at different soil depth in caragana shrubland of semiarid loess hilly region, Guyuan,China.0, 20, 40, 80 expresses soil depth of 0cm, 20cm, 40cm and 80 cm respectively.

TaTable 1 Changes of wilting coefficient with soil depths in caragana shrubland of semiarid loess hilly region of Loess Plateau, China.

Soil depth(cm)	Saturated water content (%)	Field capacity (%)	Wilting coefficient (%)	Available water content (%)
0-5	50.64	25.31	10.32	15.00
20-25	53.19	21.94	9.79	12.15
40-45	54.16	21.36	8.88	12.48
80-85	52.38	18.95	8.13	10.82
120-125	54.09	19.55	8.08	11.47
160-165	52.47	20.35	7.67	12.68
200-205	54.60	23.45	8.74	14.71
240-245	56.38	24.99	9.54	15.45
280-285	54.88	24.79	9.22	15.57
320-325	53.88	25.49	9.75	15.74
360-365	55.63	26.67	10.45	16.21
400-405	56.12	26.65	10.07	16.58

Infiltration and Infiltration depth

Infiltration is the process of water entering the soil in a certain time. After the infiltration process, there are two vertical soil water characteristics cures left on the soil profile. We can use the two vertical soil water characteristics cures to estimate infiltration depth. Before estimating infiltration depth, a neutron probe (CNC503A (DR), Beijing Nuclear Instrument Co., China) was used to monitor the changes of field volumetric soil water content (VSWC) with soil depth before a rain and after the rain event because of its high precision[6] [18-19].If we estimate the changes of soil water content with soil depth at

starting time and ending time of infiltration process in the soil profile, there is a starting vertical distribution curve of soil water before an infiltration process and an ending vertical distribution curve of soil water after the infiltration process. Two curves method was found by Guo in 2004, and used to estimate the depth of infiltration of Caragana shrubland by Guo and Shao in 2009 and Guo in 2014 [15], and named by Guo in 2020[6].

There are two vertical distribution curve of soil water after one.

The two vertical distribution curve of soil water before and after the infiltration process can be used to determine infiltration depth and soil water supply. The infiltration depth for one rain event or a given time was equal to the distance from the surface to the cross-over point between the two soil water distribution curves with soil depth before a rain event and after the rain event, and MID could be estimated by a series of two-curve methods, a set of two-curve methods[6].

Regulation of plant water relationship

As the plant grows, a seed germinates or buds, it blooms, and fruit bears and mature, and eventually leaves fall off and enter a dormant period. After finishing all these stages, plant finished a growth cycle in a growth season or about a year. The plant-water relationship in a growth cycle can be divided into two stages: period of sufficient soil moisture, in which the soil water resources within the maximum infiltration depth (MID) is more than the soil water resources use limit by plants (SWRULP) and the soil moisture is sufficient for plant growth and plant grow in healthy way, which ensure the sustainable use of soil water resources, and the period of insufficient soil moisture in which the soil water resources within the maximum infiltration depth (MID) is smaller than the soil water resource use limit by plants, which influence the plant growth, cause vegetation decline and did not ensures sustainable use of soil water resources.

Drought affects plant growth at all stages of the plant growth cycle, especially at the critical period of plant water relationship regulation because at this stage, soil water condition decides the maximum yield and benefits of forest vegetation. The plant-water relationship changes with antecedent soil water resources, soil water supply and soil water condition in the growing season. The plant-water relationship is good relation when the soil water resources in the MID is more than SWRULP and the plant grow well. When the soil water resources in the MID is less than SWRULP, soil drought is severe and affects plant growth severe. The plant-water relationship in the soil can be improved by reducing the degree of closed canopy, leaf area index and productivity by cutting or thinning trees or lopping a fruit tree based on the soil water-carrying capacity for vegetation (SWCCV) when the soil water resources within the maximum infiltration depth (MID) equal the soil water resource use limit by plants (SWRULP) in most of water limited region because of the weak self-regulation ability of exotic plants, the relationship between their growth and soil moisture cannot be regulated by self-thinning to adapt to severe soil drought and have to regulate the relationship, so it is necessary to use external force to adapt to severe soil drought.

Based on a three-year study of red plum apricot forest in the 2018 to 2020, the volumetric water content in the 0 to 290cm soil profile is more than the wilting point, and the soil water resources in the MID is more than the soil water resources use limit by plants. The 23- to 25years-old red plum apricot tree grows well and red plum apricot mature, see photo 2. Because Low Spring Temperature and frost and heart-eating harm and soil drying affect the quality and benefits of red plum apricot. Low Spring Temperature and frost often happened in the period from 1 to 18 April in spring, which influences the retention rate of flowering and young fruit and then fruit quality and benefits of red plum apricot in the Spring. Harm of Low Spring Temperature and frost on Red plum apricot often happens in Spring. Before the harm of Low Temperature and frost on Red plum apricot often happened in Spring, we have to take greenhouse or spray antifreezer to protect flowering and young fruit from Low Spring Temperature and frost; The harm of

heart-eating (*Carposina sasakii* Matsumura) on Red plum apricot often happens. If heart-eating harm happened, we should spray High-efficiency, low-toxicity Cypermethrin on the surface of young fruit and leaf to kill heart-eating worm. For example, we spray High-efficiency, low-toxicity Cypermethrin on 20 May in Guyuan, China of the semi-arid region to protect young fruit from heart-eating worm [20]. When preservation plant density is more than the soil water carrying capacity of vegetation in Spring, especially in the critical period of plant-water relationship regulation, the number of leaves and flowers or young fruit is more than the ability of natural resources to carry apricot, so we have to control the amount leaf and flowers to achieve the maximal production and beneficial result. The critical period of plant-water relationship regulation is the most important period in the plant growing period, which decided the maximal production and beneficial result of the whole growing season.

As for corn or wheat and other crop, we can increase sowing amount to ensure the preliminary plant density equals soil water carrying capacity for vegetation. When the plant density is equal to the soil water carrying capacity for vegetation, the amount of leaves and flowers or young fruit is the appropriate amount of leaves and flowers because the water-plant relationship of the fruit trees generally is regulated by lopping fruit trees, therefore, it is necessary to estimate the right amount of fruit and flowers before regulating. The heart-eating (*Carposina sasakii* Matsumura) harm on apricot fruit can be controlled by using low-toxicity and high-efficiency cypermethrin.

Soil Water Carrying Capacity for Vegetation

The idea of carrying capacity, which originated from Malthus's paper on the principle of population, is the core of sustainable development. In the early summer of 2000, the author studied the ability of soil water resources to carry vegetation in order to solve the problems of soil degradation and vegetation decay, which mainly took the form of soil drought, and to determine the reasonable limits of vegetation restoration. The concept of soil water carrying capacity for vegetation first appeared in a paper submitted by the author to the 7th Soil Physics Symposium on soil physics and ecological environment construction held by the Soil Physics Committee of Soil Society of China in Yang Ling, Shaanxi, China in December 2000[21] and then defined soil water carrying capacity for vegetation as the ability of soil water resources to carry vegetation [3] [22].

The SWCCV is the capacity of soil water resources to support vegetation, which is the maximum amount of density expressed by indicator plants in a plant population or plant community that soil water resources of a unit area can sustain and allow to grow healthily in a given period and place [9,15, 23-24].

The SWCCV in a plant community is expressed by indicator plant because vegetation is made up of different plants and there are different communities in a nation or a district or watershed and change with plant species, time scale and location [15]. An indicator plant is the constructive species for natural vegetation or main tree species for afforestation for non-native vegetation. The SWCCV can be estimated by classical carrying capacity equation and plant density - soil water model. According to the classical soil water carrying capacity equation, soil water carrying capacity for vegetation is equal to available soil water resources dividing by individual plant water requirement [15], [25]. Because plant water requirement change with weather condition, plant growth stage and soil water condition and there is not a unified definition of plant water requirement, these factors influence the application of classical soil water carrying capacity equation. According to plant density and soil water model, soil water supply reduce with plant density, at the same time, the relationship between soil water consumption and soil density is a quadratic parabola. Simultaneous solution of soil water supply - plant density relation and soil water consumption e density equation, the positive solution of the equations is the soil water carrying capacity of vegetation [15], see fig 2.

Critical period of plant-water relationship regulation

Although we can estimate soil water carrying capacity for vegetation at different time scale in the growing season in theory, but soil water carrying capacity for vegetation at different time scale have different meaning in practice. The most important time scale is critical period of plant-water relationship regulation [15].

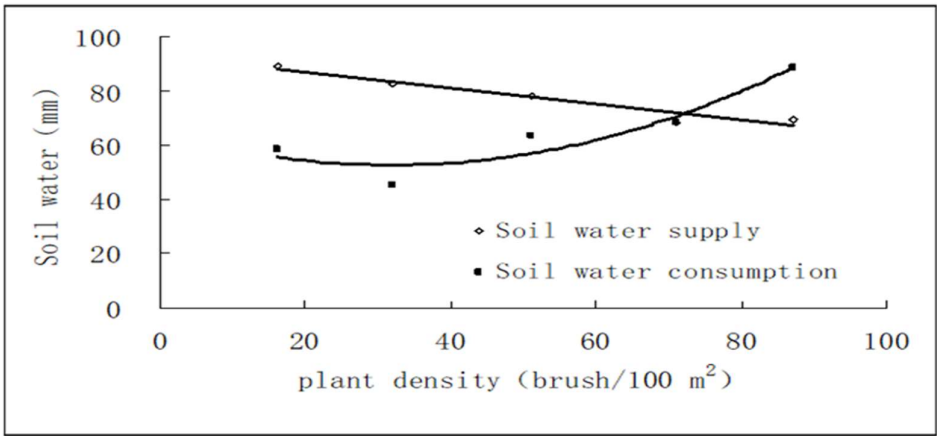


Fig.2 The relationship between plant density and soil water supply or consumption in the critical period of plant-water relationship regulation in Caragana shrubland, Guyuan, China

The starting time of the critical period of plant-water relationship regulation is the time at which the soil water resources within the MID is equal to the SWRULP. The ending time of the critical period of plant-water relationship regulation is the last day on which we can regulate the plant-water relationship based on soil water carrying capacity for vegetation and get maximum yield and benefits. The last day of the critical period of plant-water relationship regulation can be determined by thinning method. Soil degradation and vegetation degradation cannot be controlled by reducing plant density or branches after a critical period of regulation of plant-water relationship.



Photo 2 Flowers (left photo) and swollen fruits (Middle Photo) and ripe fruits (right photo) of red plum apricots in the semiarid loess hilly region, Guvuan, China

Sustainable use of soil water resources in non-native vegetation

Drought-tolerant plants generally have the ability of self-regulation. If the drought lasts less than critical period of plant-water relationship regulation, the water-plant relationship does not need to be regulated. Otherwise, in order to get the maximum yield and benefit in water limited region, we have to estimate the soil water resources use limit by plants and soil water carrying capacity for vegetation after estimating maximum infiltration depth and soil water supply and regulate the water-plant relationship based on SWCCV in the critical period of plant-water relationship regulation.

Conclusion

We must better understand and use the interaction between soil water resources and environment and plant growth because soil water resources are important part of water resources and change with rain precipitation in water-limited regions. When soil water resources in maximum infiltration depth of forest, grass or crops land reduce to soil water resources use limit by plants, especially in critical period of plant-water relationship regulation, soil water severely influences plant growth, maximum yield and benefit. At this time, the plant-water relationship should be regulated on SWCCV. In order to better manage soil water resources and environment and realize the sustainable use of soil water resources and high-quality and sustainable production of fruit crops, grassland and forest, it is necessary to master the dynamic changes of soil water and plant growth and regulating the relationship between plants and water by using soil water resources use limit by plants and SWCCV in critical period of plant-water relationship regulation of water-limited regions to ensure sustainable use of soil water resources and get the maximum yield and benefit and serve high-quality and sustainable production of fruit crops, grassland and forest.

Acknowledgements

This project is supported by National key Research & Development plan (Project No. 2016YFC0501702) and the National Science Foundation of China (Project No: National Science Foundation of China, 41071193).

Additional Information

Competing Financial Interests statement:

There is not Competing Financial and non-financial interests

References

1. Yang, W.Z., & Yu, C. Z. 1992. Regional control and evaluation in Loess Plateau. Science Press, Beijing, 190-297.
2. Li, Y. S. 2001. Effects of forest on water cycle on the Loess Plateau. Chin. Chin. J. Natural RESOUR. 6:427-432.
3. Guo, Z.S., Shao, M.A. 2003. Carrying capacity of soil water for Vegetation in the Loess Plateau. In: Water—saving agriculture and sustainable use of water and land resources. Shaanxi Science and Technology Press. 704—11.
4. Chen, H.S, Shao, M.A., & Li, Y. 2008. Soil desiccation in the Loess Plateau of China Geoderma. 143: 91-100.
5. Guo, Z.S. and Shao, M.A. 2013. Impact of afforestation density on soil and water conservation of the semiarid Loess Plateau. J. SOIL WATER CONSERV. 68, 401-410.

6. Guo, Z.S. 2020. Estimating Method of Maximum Infiltration Depth and Soil Water Supply. *Scientific Reports* volume 10, (2020) 10:9726| <https://doi.org/10.1038/s41598-020-66859-0>
7. Lvovich, M. I. 1980. Soil trend in hydrology. *Hydrological Sciences Bulletin*. 25,33-45.
8. Budagovski, A.I. 1985. Soil water resources and water supplies of plant cover, *Vodnye Resursy*, 4, 3-13
9. Guo, Z.S. 2011. A review of soil water carrying capacity for vegetation in Water-limited regions. *Chinese Journal of Forestry Sciences*. 47 (5):140-144.
10. Palmer, W.C. 1968. Keeping track of crop moisture conditions, nationwide: the new crop moisture index. *Weatherwise*. 21,156-61.
11. Shi, J., Li, S., Zuo, Q., Ben-Gal, A. 2015. An index for plant water deficit based on root-weighted soil water content. *J. Hydrol*, 522,285–94.
12. McKee, T.B., Doesken, N.J., Kleist, J. 1993. The relationship of drought frequency and duration to time scales. In: *Eighth Conference on Applied Climatology*. American Meteorological Society, Anaheim, CA, 179-184.
13. Martínez-Fernández, J. , González-Zamor, A., Sánchez, N., Gumuzzio, A. 2015. A soil water based index as a suitable agricultural drought indicator. *J. Hydrol.*, 522,265–273.
14. Guo Z.S. Soil water resource use limit in semi-arid loess hilly area. *Chin J Applied Ecol*. 2010, 21, 3029–35.
15. Guo, Z.S. 2014. *Theory and Practice on Soil Water Carrying Capacity for Vegetation*. Chinese Science Press: website at www.geobooks.com.cn.
16. Guo, Z.S. and Shao, M.A. 2009. Soil water infiltrating process in afforested land on slopes of semiarid region of loess plateau. *ACTA pedologica Sinica*. 46 (5):953-958. <http://www.doc88.com/p-1197289823160.html>.
17. Richards, L.R. Weaver. 1943. Fifteen atmosphere percentage as related to the permanent wilting percentage. *Soil Science*, 56:331–339.
18. Wang, G.Y., Shi, X.P., Zhang, J.H., Liang, W.L. 2000. A study on the comparison of measuring soil water content with TDR, neutron probe and oven dry. *Chin. J. Agr. University of Hebei* 23:23-26.
19. Evett S.R., Schwartz R.C., Casanova J.J., Heng L.K. 2012. Soil water sensing for water balance, ET and WUE. *Agr Water Manage*. 104:1-9
20. Guo, Z.S. 2013. Garden economy industrialization in semiarid loess hill regions. *Practical forestry technology*, (9):82-94
21. Guo, Z.S., Shao, M.A., Zhang, Y.P. and Wu, Q.X. 2002. A Layer-dividing method to soil water in forest land, *Proceedings of soil physics and ecological environment construction*, edited by Shao MA, Shaanxi Science and technology press, 75-79
22. Wang, Y., Yu, P., Xiong, W., Shen, Z., et al. 2008. Water-yield Reduction after Afforestation and related Processes in the semiarid Liupan Mountains, Northwest China. *Journal of the American Water Resources Association*. 44(5): 1086-1097

23. Guo, Z., & Shao, M. 2004. Mathematical model for determining vegetation carrying capacity of soil water. J. Hydr. 35 (10), 95–99. [http://doi: 10.3321 /j.issn: 0559-9350.2004.10.015](http://doi:10.3321/j.issn:0559-9350.2004.10.015)

24. Xia, Y. & Shao, M. 2008. Soil water carrying capacity for vegetation: a hydrologic and biogeochemical process model solution. ECOL MODEL, 214,112–124. <https://doi.org/10.1016/j.ecolmodel.2008.01.024>

25. Cohen, J.E.1995. Population Growth and Earth's human carrying capacity.Science, 54:213-229