Rainwater efficient use of the cellar-greenhouse system on slope land in hilly semi-arid area of North China

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ABSTRACT

Water resources in semi-arid and arid regions are the most strongly limiting factor of the growth for plants. Rainwater efficient use is one of the focuses of the water resources research. In this paper, an experiment was conducted at Ka Zuo Research Station of Ecological Agriculture, Institute of Applied Ecology, Chinese Academy of Sciences in the hilly semi-arid area of North China. It aimed at studying the efficient use of rainwater harvesting of the cellar-greenhouse system (CGS). Results showed that, on average, the rainwater harvesting efficiency and sediment yield of the CGS were 5.7–15.7% and 865.8–1794.0 kg/ha, respectively, and that the rainwater harvesting efficiency and sediment yield of the CGS on slopes of 6° and 7° were significantly higher than that of the CGS on slope of 4.5°. In the CGS, over 52.1% of the irrigation rainwater was saved; the irrigation efficiency was significantly improved, by 21.15 kg/m^3/ha on average, for sub-surface irrigation. Moreover, compared with flood irrigation, sub-surface irrigation could increase vegetable yield by 8.1–22.3%, improve output value of rainwater by 116.8–164.6%, and furthermore, the environmental conditions of the greenhouse on slope land were improved obviously. The mean unit area value of the CGS was about 13.5 times higher than that of the traditional land use system. By using the CGS, three goals, which were reducing water and soil losses, getting high rainwater use efficiency and gaining corresponding benefits, were realized.

Keywords: rainwater harvesting; cellar-greenhouse system (CGS); greenhouse on slope land; sub-surface irrigation; hilly semi-arid area

Water crisis is one of the major environmental concerns in the world. Especially in the semi-arid and arid regions, water resources are the most strongly limiting factor of the growth for plants (Arora et al. 1987, David and Howes 2003). Rainwater efficient use is one of the focuses of the water resources research (Li et al. 2006, Trnka et al. 2007).

The hilly semi-arid area is situated in the contiguous area among the provinces of Liaoning, Hebei and Inner Mongolia and their surrounding regions of North China, and covers about 1.1×10^7 ha. It is the main rainwater-fed farming region in China. Rainwater-fed cropland occupies about 80% of the total cultivated land in the hilly semi-arid area. Loosely structured soil, high susceptibility to water and wind erosion, low rainfall and uneven distribution are dominant factors. This is a fragile eco-environment, with limited sustainable development of agriculture and animal husbandry. Although the farming techniques of the protective cultivation and terrace help to maintain soil moisture and increase output, the drought and shortage of water could not be solved by those single techniques. It may cause sowing late and hardly developing efficient agriculture and productive potential of land resource. Therefore, shortage of water and serious water and soil loss are limiting the sustainable agriculture development in the area (Li 2004). It is the key measurement for promoting the regional sustainable agriculture development and ecological construction to en-

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hance the rainwater harvesting efficiency and to control soil erosion (Liu and Mu 2005).

Based on these conditions, rainwater harvesting techniques were stimulated, and the term rainwater harvesting agriculture (RHA) was put forward by Zhao Song-ling (1996). The RHA system consists of catchments, runoff channels, sediment pool, storage containers and supplemental irrigation systems (Wu et al. 2002). The aim is to increase the effective water for crop growth through capturing rainwater. Studies show that rainwater harvesting offers an effective method of improving agricultural conditions of semi-arid area (Wei and Bai 2002). The climate and geography of semi-arid area of North China are favourable for the RHA development (Li 2002). RHA suits a rural family garden using concrete courts, rooftops and roads for rainwater harvesting. It supplies household water needs and permits the surplus water to be used for irrigation of fruit trees, vegetable and small scale crop land (Feng and Qian 2001, Blaine et al. 2006, Liu 2006). Value of vegetable output in a greenhouse produced with irrigation using rainwater harvesting is higher than that of field crops or fruits irrigated using the same volume of rainwater harvesting (Li et al. 2003, Cao 2004). However, few systematic studies have been conducted on rainwater harvesting of the cellar-greenhouse system (CGS).

China's greenhouse is different from that of the developed countries and represents an innovation for year-round vegetable cultivation in China's arid and semi-arid regions. The term greenhouse identifies the sole dependence on solar power for heating. This technique has been extensively applied in China's cold northern areas between latitudes 30°–44°N. Many vegetables can be successfully cultured not only in spring and summer but also in winter in China's cold areas without need for artificial heating. Area of greenhouse in China was said to have reached 380 000 ha (Zhang and Li 2006). Especially, many greenhouses in the hilly semi-arid area were built on the slope land, which can not only control the soil erosion but also enhance the slope land productivity (Gao and Liu 2004). China's area of such cultivation has become the largest in the world. The average per capital consumption of vegetable supplied by greenhouse is over 27.6% of total vegetable consumption. However, most semi-arid regions of North China are suffering from a shortage of water, which hinders the development of greenhouses there. Water shortage in winter is still a limiting factor in using greenhouses.

So far, few studies have been performed where rainwater harvesting was used for water-saving irrigation greenhouse on slope land. In this study, the probability of further exploiting RHA in the semi-arid area of North China is investigated, including selection of catchments, storage of rainwater harvesting and its effective use for water-saving irrigation vegetables in greenhouses on slope land.

MATERIAL AND METHODS

Study area and environmental conditions. The study was conducted at the Ka Zuo Research Station of Ecological Agriculture, Institute of Applied Ecology, Chinese Academy of Sciences, during the years 2005, 2006 and 2007. The study area is located in the western part of Liaoning province, which is the typical hilly semi-arid area of North China, between latitudes 40°24′30′′–42°20′42′′N and longitudes 118°50′19′′–121°17′36′′E (Figure 1). The regional climate is semi-arid, with mean annual precipitation of about 475 mm and nearly 75% falling between May and September. Average annual evaporation is 2.140 mm. Mean annual temperature is 8.2°C. Mean annual sunshine hours are 2.900 h, and the effective accumulated temperature above 0°C and 10°C are 3839.4°C and 3431.8°C, respectively (Yan 2000). The frost-free period is 152 days. Soil type is cinnamon soil with the organic matter under 10 g/kg in the top 0.1 m layer, and soil pH value ranges from 5.9 to 8.5. The main crops are maize, millet and sorghum, and their yields are low due to aridity and serious soil erosion.

Figure 1. Study areas shown in the map (the dot in the map is the area of the CGS)

Design of the CGS. The term cellar-greenhouse system (CGS) is used for the system where rainwater was collected and stored in the cellars and then used for water-saving irrigation the greenhouse on slope land. So the CGS are made up of four parts (Figure 2), including a rainwater-collecting site, sediment pool for depositing sand, rainwater cellar and a greenhouse on slope land. It combines principles of technological integration of rainwater harvesting, accumulative storage and efficient use.

In the hilly semi-arid area of North China, the hillside is not only the major site of surface runoff production, but also the main area of soil erosion. Some protective cultivation measures have been used to hold up runoff for hillside erosion harness, but there is still a large amount of surface runoff on hillside. Moreover, there are a lot of uncontrolled hillside land and slope fields. All of these are potential rainwater harvesting grounds, so the CGS was constructed for storage of which can be used to irrigate the greenhouse on hillside. The volume and numbers of the CGS can be determined based on the area of hillside and the total amount of rainwater collected. The rainwater harvesting potential of the CGS can be estimated using the following formula:

$$W = R \cdot K_p \cdot P_0 \cdot S/1000$$

where: W – rainwater harvesting potential (m^3), R – runoff coefficient, K_p – modular coefficient, P_0 – mean annual precipitation (mm), S – area of rainwater collecting ground (m^2)

Greenhouse and irrigation experiments. The greenhouse on slope land consists of a back wall, sidewall, back roofing, arch truss, plastic mulch, winter protection channel and warming cover material. The intermediate distance between greenhouses is 9–10 m. Basin dimensions are 7 × 1 m, with irrigation supply pipes at 1 m spacing inside greenhouses of 50 × 7 m (0.035 ha) on hillside fields. The grown crops were cucumber and tomato.

Both sub-surface irrigation and flood irrigation were adopted in the rainwater harvesting irrigation experiments. For the two irrigation methods, the soil moisture rate was measured with the oven-dry method; soil bulk density was determined by using soil corer and measuring the weight of dry soil (Hua and Wang 2003) of a unit volume to a depth of 0–0.1 m, 0.1–0.2 m, 0.2–0.3 m and 0.3–0.4 m soil depth separately. Soil porosity, soil temperature, air relative humidity and daily evaporation capacity were also measured by the ordinal methods (Luo 2001). At the same times, the irrigation amount, crop growth condition, disease generation rate and crop yield were also measured. Economic benefit and output value of rainwater were calculated for each irrigation method.

Runoff and sediment. The amount of runoff was measured by the sediment pool, automatic water-stage recorder and triangular measuring weir (Hammecker et al. 2003). The amount of sediment was the sum of the dry weight of suspended load and the dry weight of tractional load. The dry weight of suspended load was the sand being filtrated from the runoff sample, and the dry weight of tractional load was the depositing sand in the sediment pool (Qin 2003).

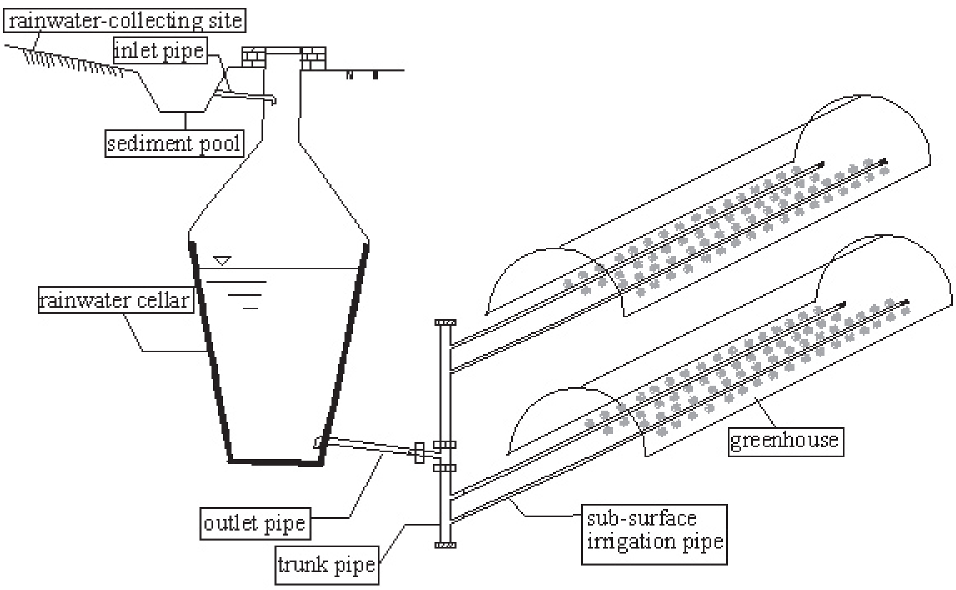

Figure 2. The design chart of the cellar-greenhouse system (CGS)

Statistical analyses. To observe effects of runoff, sediment and rainwater irrigation of the CGS for different irrigation methods, the statistical analyses were conducted by using SPSS-PC statistical software (Lu 2005) and Excel statistical software (Wang 2003).

RESULTS AND DISCUSSION

Rainwater harvesting efficiency

Rainwater harvesting efficiency means the ratio of annual collected rainwater runoff capacity in relation to annual effective rainfall (effective rainfall means that can generate surface runoff). Table 1 suggested that annual rainwater harvesting efficiency of the CGS was 5.7–15.7%. The CGS could only collect surface runoff from several of the larger rainfall events because some little rainfall could not generate surface runoff. ANOVA indicated that annual rainwater harvesting efficiency of the CGS on slopes of 6° and 7° were significantly higher than that of the CGS on slope of 4.5° ($F = 19.15 > F_{0.01} = 5.95$, $P < 0.002$ for the CGS on slopes of 6° and 4.5°; $F = 24.27 > F_{0.01} = 5.95$, $P < 0.001$ for the CGS on slopes of 7° and 4.5°). However, no significant differences were found for the CGS on slopes of 7° and 6° ($F = 3.67$, $F_{0.05} = 3.49$, $P < 0.084$) and for the CGS on the same slopes (i.e. $F = 3.38 < F_{0.05} = 3.49$, $P < 0.0706$ for CGS-1 and CGS 6; $F = 3.15 < F_{0.05} = 3.49$, $P < 0.0935$ for CGS-2 and CGS-4; $F = 3.07 < F_{0.05} = 3.49$, $P < 0.0987$ for CGS-3 and CGS-4). Table 1 also showed that the rainwater harvesting efficiencies of the CGS had a significant positive correlation to the slope of the CGS. So the CGS of slope greater than that of 6° is recommended for rainwater collection sites in order to gain enough amount of runoff.

Sediment deposition

Rainwater was not only collected through the CGS but it also accumulated sediment. Table 1 showed that annual sediment yield of the CGS were about 865.8–1794.0 kg/ha, and annual mean sediment yield of the CGS was 1429.0 kg/ha. ANOVA indicated that annual sediment yield of the CGS on slopes of 6° and 7° were significantly higher than that of the CGS on slope of 4.5° ($F = 89.37 > F_{0.01} = 5.95$, $P < 0.003$ for the CGS on slopes of 6° and 4.5°; $F = 95.14 > F_{0.01} = 5.95$, $P < 0.002$ for the CGS on slopes of 7° and 4.5°). However, no significant differences were found for the CGS on slopes of 7°and 6° ($F = 2.27 < F_{0.05} = 3.49$, $P < 0.0812$) and for the CGS on the same slopes. So the CGS of slope greater than that of 6° is recommended in order to gain enough amount of rainwater and sediment deposition. It showed that the CGS could integrate technology of rainwater harvesting with soil erosion control.

Irrigation efficiency of rainwater harvesting

In the rainwater harvesting irrigation experiments, two irrigation methods, sub-surface irrigation and flood irrigation, were adopted to irrigate the greenhouse with collected rainwater. Results

Table 1. Effects of rainwater harvesting and sediment deposit of the CGS (2005–2007*)

Number of the CGS	Area of rainwater collecting site (ha)	Slope (°)	Annual effective rainfall (mm)	Annual collected runoff (m^3)	Annual deposited sediment (kg)	Annual rainwater harvesting efficiency** (%)	Annual sediment yield*** (kg/ha)
CGS-1	0.50	4.5	377.3	136.30 ± 12.3^a	432.9 ± 20.4^a	7.2 ± 0.45^a	865.8 ± 25.3^a
CGS-2	0.30	7.0	377.3	178.12 ± 16.4^b	538.2 ± 23.2^b	15.7 ± 1.23^b	1794.0 ± 58.9^b
CGS-3	0.52	6.0	377.3	238.10 ± 20.8^b	894.2 ± 29.3^b	12.1 ± 0.89^b	1719.6 ± 47.6^b
CGS-4	0.40	6.0	377.3	164.88 ± 14.2^b	617.4 ± 27.8^b	10.9 ± 0.78^b	1543.5 ± 43.2^b
CGS-5	0.35	7.0	377.3	199.24 ± 17.3^b	610.5 ± 25.1^b	15.1 ± 1.04^b	1744.3 ± 50.8^b
CGS-6	0.42	4.5	377.3	89.77 ± 9.7^a	380.9 ± 18.6^a	5.7 ± 0.34^a	906.9 ± 28.1^a

*the numbers in Table 1 are the means of the three years (2005, 2006 and 2007); **annual rainwater harvesting efficiency (%) = 10 × annual collected runoff/annual effective rainfall × area of rainwater-collecting site; ***annual sediment yield (kg/ha) = annual deposited sediment/area of rainwater collecting site

Table 2. Irrigation amount and irrigation efficiency of the CGS (2005–2007)

Vegetable species	Net area of greenhouse (ha)	Irrigation method	Irrigation frequency (times)	One irrigation amount (m^3)	Irrigation quota (m^3/ha)	Yield (kg/ha)	Irrigation efficiency (kg/m^3/ha)
Cucumber 1	0.035	flood irrigation	20	8.03	4590 ± 125.1^a	57714.3 ± 237.3^a	12.57 ± 1.51^a
Cucumber 2	0.035	sub-surface irrigation	37	2.01	2130 ± 78.5^b	70571.4 ± 315.7^b	33.13 ± 2.24^b
Tomato 1	0.035	flood irrigation	14	8.18	3270 ± 105.8^a	61142.9 ± 247.4^a	18.69 ± 1.69^a
Tomato 2	0.035	sub-surface irrigation	34	1.68	1635 ± 62.5^b	66114.3 ± 285.2^b	40.43 ± 2.88^b

Table 3. Influence on environmental factors of different irrigation ways of the CGS* (2005–2007)

Vegetable species	Irrigation method	Soil bulk density (g/cm^3)**	Total soil porosity (%)**	Soil temperature (°C)	Air relative humidity (%)	Daily evaporation capacity (mm)	Disease occurrence frequency (times)
Cucumber	flood irrigation	1.42 ± 0.12^a	42.8 ± 3.15^a	20.8 ± 1.58^a	90.0 ± 5.65^a	2.50 ± 0.21^a	4
Cucumber	sub-surface irrigation	1.20 ± 0.08^b	52.4 ± 2.62^b	22.2 ± 1.87^b	80.0 ± 4.69^b	1.01 ± 0.07^b	1

*background value: soil bulk density 1.19 g/cm^3; total soil porosity 53.3%; **soil bulk density and total soil porosity are the mean values of the soil depths of 0–0.1 m, 0.1–0.2 m, 0.2–0.3 m and 0.3–0.4 m separately

indicated that the irrigation quotas of cucumber and tomato for flood irrigation were 4590 m^3/ha and 3270 m^3/ha, respectively (Table 2). However, the irrigation quotas of cucumber and tomato for sub-surface irrigation were 2.130 m^3/ha·and 1.635 m^3/ha, respectively (Table 2); ANOVA indicated, compared with flood irrigation, that over 52.1% of the irrigation rainwater was saved with sub-surface irrigation (cucumber: $F = 197.09 > F_{0.01} = 6.99$, $P < 0.001$; tomato: $F = 178.57 > F_{0.01} = 6.99$, $P < 0.001$) (Figure 3). Table 2 also showed that the mean irrigation efficiency for flood irrigation and sub-surface irrigation were 15.63 kg/m^3/ha (cucumber 12.57 kg/m^3/ha; tomato 18.69 kg/m^3/ha) and 36.78 kg/m^3/ha (cucumber 33.13 kg/m^3/ha; tomato 40.43 kg/m^3/ha), respectively. ANOVA indicated that compared with flood irrigation, the irrigation efficiency of sub-surface irrigation was significantly improved, by 21.15 kg/m^3/ha on average (cucumber $F = 75.64 > F_{0.01} = 6.99$, $P < 0.001$; tomato $F = 57.85 > F_{0.01} = 6.99$, $P < 0.001$) (Figure 4). Therefore, the rainwater-saving effect of sub-surface irrigation was better than that of flood irrigation (Camp 1998).

Influence on environmental factors

Table 3 showed influence of sub-surface irrigation and flood irrigation of the CGS on environmental factors. ANOVA indicated that the influence on

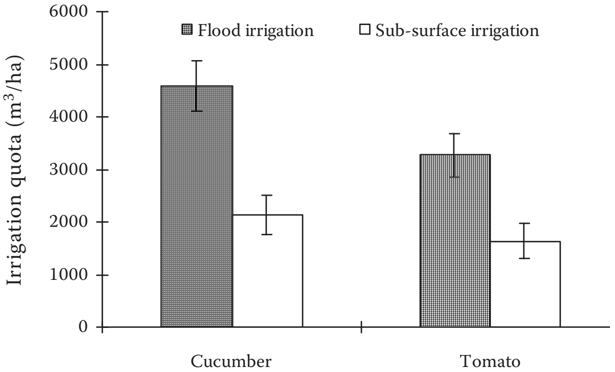

Figure 3. Irrigation quotas for different irrigation ways of the CGS

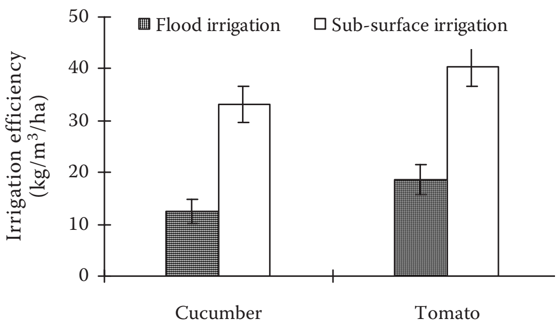

Figure 4. Irrigation efficiency for different irrigation methods of the CGS

Table 4. Economic benefits of different irrigation methods of the CGS*

Vegetable crops	Total area of the CGS (ha)**	Area of greenhouse (ha)**	Irrigation methods	Irrigation amount (m^3)	Yield (kg)	Economic benefit (CNY)	Output value of rainwater (CNY/m^3)
Cucumber 1	0.06667	0.035	flood irrigation	160.6 ± 4.24^a	2020 ± 14.62^a	4040 ± 22.3^a	25.16 ± 3.12^a
Cucumber 2	0.06667	0.035	sub-surface irrigation	74.2 ± 2.23^b	2470 ± 18.36^b	4940 ± 29.35^b	66.58 ± 4.69^b
Tomato 1	0.06667	0.035	flood irrigation	114.5 ± 3.65^a	2140 ± 13.24^a	4066 ± 6.38^a	35.51 ± 3.27^a
Tomato 2	0.06667	0.035	sub-surface irrigation	57.1 ± 1.87^b	2314 ± 16.71^b	4396 ± 27.51^b	76.99 ± 4.91^b

*cucumber: 2.00 CNY (RMB)/kg; tomato: 1.90 CNY (RMB)/kg; **the total area of the CGS (including the area of sediment pool; rainwater-cellar and greenhouse) is 0.06667 ha (1 mu); the area of the greenhouse (for cropping vegetable) is 0.035 ha (50 × 7 m)

environmental factors between sub-surface irrigation and flood irrigation significantly differed (Gao et al. 2008), i.e. compared with the flood irrigation, sub-surface method had soil bulk density lower by 15.5% ($F = 14.91 > F_{0.01} = 11.26$, $P < 0.005$), soil porosity improved by 22.4% ($F = 21.71 > F_{0.01} = 11.26$, $P < 0.002$), soil temperatures increased by 6.7% ($F = 17.89 > F_{0.01} = 11.26$, $P < 0.003$), air relative humidity lower by 11.1%, ($F = 19.3 > F_{0.01} = 11.26$, $P < 0.002$) and daily evaporation capacity decreased by 59.6% ($F = 24.19 > F_{0.01} = 11.26$, $P < 0.001$). Therefore, sub-surface irrigation was superior to flood irrigation with respect to improving ecological environment factors of the greenhouse, and it also prompted a 75% reduction in vegetable disease. This means lower cost and an improved quality of vegetables entering the market early.

Economic benefits of the CGS

Using form of slope land was changed by the CGS and productivity was increased to a great extent. The CGS (total area of the CGS is 0.06667 ha)

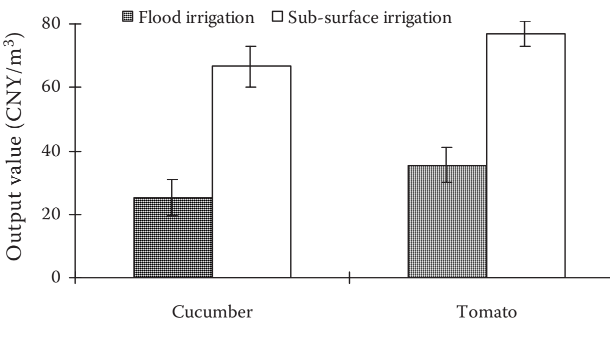

Figure 5. Output value of water for different irrigation ways of the CGS

could produce 2245.0 kg (flood irrigation 2020 kg; sub-surface irrigation 2470 kg) of cucumbers and 2227.0 kg (flood irrigation 2140 kg; sub-surface irrigation 2314 kg) of tomatoes, valued at 4490.00 CNY (RMB) and 4231.30 CNY (RMB), respectively (Table 4). Compare with the traditional land use system for the sloping field (the same area unit yield of corn for the sloping field was 300 kg; the mean area value was 300.00 CNY (RMB); Corn: 1.00 CNY (RMB)/kg), the mean unit area value of the CGS was 4360.65 CNY (RMB), which was about 13.5 times higher than that of the traditional land use system. Moreover, ANOVA showed that the influence of irrigation methods on economic benefits was significantly different, i.e. sub-surface irrigation increased vegetable yield by 8.1–22.3% (cucumber $F = 27.09 > F_{0.05} = 5.32$, $P < 0.018$; tomato $F = 18.14 > F_{0.05} = 5.32$, $P < 0.021$), improved output value of rainwater by 116.8–164.6% (cucumber $F = 30.16 > F_{0.01} = 11.26$, $P < 0.002$; tomato $F = 28.04 > F_{0.01} = 11.26$, $P < 0.003$) (Figure 5). Therefore, sub-surface irrigation should be applied in irrigating greenhouse on slope land, which could produce larger economic benefits (Pascual et al. 2006).

The CGS is a new exploration of effective use of rainwater harvesting. By the CGS, the greenhouse on slope land can be utilized further, and rainwater can be used effectively from the changing of time and space distribution of rainfall. With the CGS, the installation agriculture can be exploited in hilly semi-arid area of North China, and produce high value products in cold seasons.

The experiment area of North China has a large area of slope land, with small amounts of concentrated rainfall and soil and water loss is very serious there. Hence the natural conditions are advantageous for rainwater collection and storage, and RHA has a broad appeal in the area. The

CGS cannot only meet the irrigation demand of cucumber or tomato, etc., but it can obviously reduce water and soil loss on slope land. The goals of reducing water and soil loss, achieving high rainwater use efficiency and economic benefit can be thus met with the CGS.

The studies of the CGS are preliminary at present, the materials of catchments, storage and effective use techniques of rainwater harvesting should be further researched. Moreover, the environment-improving effects of the CGS for different irrigation ways should be also investigated in future.

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