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Soil Water Carrying Capacity for Vegetation

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23 **Abstract**

24 Non-native plantation can effectively conserve soil and water and improve ecological
 25 environment , but soil desiccation occurs and then changes to severe desiccation in
 26 most forest and grass lands of water-limited regions, which causes soil degradation,
 27 vegetation decline and crop failure, so it is necessary to regulate the changed
 28 relationship between plant growth and soil water. However, there is a lack of a
 29 universally accepted theory to provide guidance of sustainable use of soil water
 30 resources and sustainable management of forest and sustainable produce of crop in
 31 such regions. The theory of regulating the relationship between plant growth and soil
 32 water in water-limited regions includes the Soil Water Resources Use Limit by Plant
 33 (SWRULP) and Soil Water Carrying Capacity for Vegetation (SWCCV) . The
 34 SWCCV is the population in a plant population or density of indicator plants in a
 35 plant community when the soil water supply is equal to soil water consumption in
 36 the root zone and a given time, and changes with plant community type, location and
 37 time. The degree of coverage, productivity and benefits of a plant community when
 38 population quantity of an indicator plant equals SWCCV should be the theoretical
 39 basis for ensuring sustainable use of soil water resources and sustainable
 40 development of forest.

41 *Keywords:* Water-limited regions; Soil desiccation; Soil degradation; vegetation
 42 decline , Soil water resources ; maximum infiltration depth , Soil water resources use
 43 limit by plant; Soil water carrying capacity for vegetation; sustainable use of soil
 44 water resources; sustainable development of forest ; sustainable produce of crop

45 **1 . Introduction**

46 In most parts of the world, human activities, such as overgrazing, deforestation,
 47 denudation and reclamation have greatly altered the type of vegetation that dominates
 48 the landscape. These have accompanied the demand for food, timber and biofuels due
 49 to local population increases, which historically have frequently occurred in
 50 water-limited regions such as the Loess Plateau of China. Intense and poorly managed
 51 agricultural practices have often caused a decline in the density of natural plant
 52 populations (Metcalfe and Kunin 2006) . Consequently, the original vegetation has
 53 disappeared and there has been a decrease in the level of forest cover and in the ability
 54 of forests to maintain a balanced ecosystem. Such changes have led to severe soil and
 55 water loss and continual degradation of the natural environment on the Loess Plateau,
 56 which severely affects the health and security of forest and vegetation ecosystems and
 57 humans.

58 In order to conserve soil and water and improve the ecological environment and
 59 restore harmonious human–human, human–nature and human–society relationships
 60 (i.e. ecological civilization construction), since 1950, large-scale afforestation has
 61 been carried out on the Loess Plateau. This has been especially supported since 1978
 62 by implementation of projects of the ‘Three-north Protection Forest’ that involves
 63 planting trees and establishing protection forest in north-eastern, north-western and
 64 northern regions of China to control soil and water loss, prevent wind erosion and fix
 65 sand and improve the ecological environment in which people live and work. The
 66 ‘Converting Farmland to Forest’ has also been implemented since 2000 and

strengthened vegetation restoration. Consequently, forest area and coverage has dramatically increased, as has the efficiency of forest and vegetation in conserving soil and water. For example, the sediment discharge on the Loess Plateau was reduced from 1.6 billion tonnes per year in the 1970s to 0.3 billion tonnes per year in recent years, runoff has halved and the environment has improved. The efficiency of forest and vegetation accounts for more than half of the total efficiency.

In the process of vegetation restoration, tree species, selected for their capacity to extend deep roots and for fast growth, were planted at high initial planting densities to rapidly establish high degrees of ground cover and higher biomass and yields, and thereby to quickly realize ecological, economic and social benefits during vegetation restoration. It is advantageous that the roots of these plants grow quickly and thus they take up water from considerable soil depths, such as 5.0 m for 16-year-old *Caragana* (*Caragana korshinskii* Kom.) of the semiarid loess hilly region in Guyuan County, Ningxia Hui Autonomous Region of China and 22.4 m for 23-year-old *Caragana* (*C. microphylla* Lam.), another related species in Suide County, Shaanxi Province of China (Wang *et al* 2009). However, soil water mainly comes from precipitation; and the maximum infiltration depth (MID) and soil water supplies are limited in this region (Guo and Shao 2013). Thus, root depth can exceed the depth of soil water recharge from rainwater, leading to severe desiccation of soil in rooting soil layers (Wang *et al* 2009 ;Guo and Shao 2003). Consequently, the combination of increased water use by plants and low water recharge rates has led to soil deterioration, receding vegetation and crop failures on the Loess Plateau or other water-limited regions in the

89 perennial artificial grass and forest land(Yang 1996 ; Li 2001 ; Chen et al 2007). Such
 90 soil deterioration can adversely affect ecosystem function and services and the
 91 stability of man-made forest and vegetation ecosystems, and consequently reduces the
 92 ecological, economic and societal benefits of forest and other plant communities. In
 93 turn, this suggests that the relationship between plant growth and soil water
 94 (RBPGSW) in these perennial artificial grass and forest lands is not balanced and
 95 should be controlled.

96 Managing an ecological system to maximize the benefits of vegetation requires
 97 establishing a balance between soil water supply and soil water consumption over a
 98 long time in water-limited regions. This is because a rapid increase in density and the
 99 degree of coverage of forest and/or other plant communities not only effectively
 100 increases coverage and reduces runoff and erosion(Bosch and Hewlett 1982 ; Khanna
 101 et al 1999 ; Gardiol *et al* 2003 ; Dijk and Bruijnzeel 2003 ; Anderegg *et al* 2012) but
 102 also reduces soil water supply and increases soil water consumption by vegetation and
 103 evapotranspiration(Kyushik *et al* 2005), which can lead to imbalance in the RBPGSW.
 104 Therefore, there should be limits to vegetation restoration in a region where the
 105 natural resources (including water, soil water, soil nutrients or land resources) are
 106 scarce. The limit would depend on the capacity of the available natural resources in an
 107 ecosystem to support vegetation, i.e., land carrying capacity for vegetation or
 108 vegetation carrying capacity (Guo and Shao 2003) .

109 Water is the main factor affecting vegetation restoration in most water-limited
 110 regions. The carrying capacity of land for vegetation in this region is soil water

111 carrying capacity for vegetation (SWCCV) (Guo *et al* 2002 ;Guo and Shao 2003) –
 112 the ability of soil water resources to support vegetation. Therefore, the balance
 113 between the consumption and supply of water to the soil should be considered when
 114 restoring vegetation cover in order to realize the goal of soil and water conservation
 115 and sustainable use of soil water resources.

116 The Loess Plateau has the most serious soil and water losses in the world. It is
 117 located in the centre of China, and has an area of 642 000 km² of which 454 000 km²
 118 experiences soil and water loss and has scarce water resources. Soil in this region is
 119 very deep, in the range of 30–80 m from the surface (Zhu *et al* 1983) , and the
 120 groundwater table is also deep (Yang and Shao 2000) . Without irrigation, the best
 121 measure to solve issues of soil degradation and vegetation decline is to regulate the
 122 RBPGSW by reducing the population quantity of indicator plants in a plant
 123 community to match SWCCV on the Loess Plateau, thus balancing the soil water
 124 recharge and soil water consumption in plantations (Guo an shao 2003) .

125 Drought is a recurring natural phenomenon. The complex nature and widespread
 126 impact of drought on forest and grass land with high coverage and production –
 127 driven by artificial vegetation consuming more than a permissible quantity of soil
 128 water resources in water-limited regions – means that regulating the RBPGSW is
 129 needed to maintain soil water consumption of restoring vegetation at levels that
 130 sustainably use the soil water resources. However, there is a lack of a universally
 131 accepted theory to provide guidance for regulating the RBPGSW in forest and grass
 132 land in these regions. We aimed to develop the theory for regulating the RBPGSW in

133 forest and grass land in water-limited regions, including (1) the concepts of soil water
134 resources, (2) soil water resource use limits for plants, (3) SWCCV, (4) basic laws of
135 SWCCV and (5) the use of SWCCV in the sustainable management of forest and
136 vegetation.

137 **2 . Soil water resources**

138 Soil water is the water existing in the soil space. Soil water cannot be transferred by
139 humans from one place to another but can be used by plants. Soil can hold much
140 water and this is sometimes termed a soil reservoir. The amount of water held in the
141 soil is the soil water resource. Soil water resources come (Budagovski 1985) after the
142 overall soil moistening (Lvovich , 1980). Soil water resources is the water stored in
143 the soil from surface soil to the groundwater table- generalized soil water resources or
144 the water stored in the root zone soil- Soil water resources in narrow sense, and the
145 dynamic soil water resources - the antecedent soil storage in the root zone plus the soil
146 water supply from precipitation in the plant growing period or a year for evergreen
147 plants – because soil water from precipitation in the growing season can be taken up
148 immediately by live plants and influence their growth.

149 Plant evapotranspiration including plant transpiration and film water evaporation on
150 the surfaces of leaves, branches and stems when raining and after a rain event is a
151 hydrological effect that induces soil suction. With water absorption by roots and
152 evapotranspiration, soil water content and soil water potential are reduced but soil
153 water suction is increased. When soil water content in every soil layer is reduced to
154 the wilting coefficient, the suction of soil particles to water exceeds that of plants to

155 soil water and the water stored in all soil layers cannot be further taken up by plants
156 (i.e. it is plant-unavailable). When soil water content in every soil layer is higher than
157 wilting coefficient, the suction of soil particle to water is lower than that of plants to
158 soil water and so this part of soil water resources is plant-available and can be sucked
159 by plant.

160 **3 . Soil Water Resource Use Limit by Plants**

161 A tree or plant is a complex organism with a series of regulatory mechanisms to keep
162 vital systems operating within appropriate restrictions, and with mechanisms to repair
163 damage that may occur when these limits are exceeded. A tree or plant transports
164 water from the soil to the atmosphere along a water potential gradient; its survival
165 depends on maintenance of this transport system (Anderegg *et al* 2012) . Plants also
166 have some self-regulation function in the opening degree of stomata in leaves and the
167 number of leaves retained during water stress; however, this self-adjustment is limited
168 and cannot meet the need of regulating RBPGSW in the process of plant growth in
169 some extreme conditions, such as severe drought and hot days on the Loess Plateau.
170 While a plant grows, individual size expands, Canopies effect on soil water supply
171 and soil water consumption strengthens and roots deepen but soil water resources in
172 artificial forest and grass land often decline in water-limited regions, even if there are
173 some increases after rain events, and then root water uptake declines. Water stress
174 begins when transpiration demand exceeds root water uptake, resulting in a loss of
175 turgor. Subsequent short- and long-term responses include declines in cell
176 enlargement and leaf expansion rate, reduced photosynthesis and transpiration, and

177 alterations in phenology, senescence, carbon allocation and ultimately reduced yield
178 and water use efficiency. When soil water resources reduce to the degree, that results
179 in severe soil drought, and finally leads to soil degradation, plant growth ceases and
180 vegetation recedes or even dies in artificial forest and grass land.

181 The RBPGSW is important for the prevention of further soil drying and soil
182 degradation and the sustainable use of soil water resources and sustainable
183 management of forest vegetation in water-limited regions. In practice, regulating the
184 RBPGSW is not required once soil drought happens in forest and grass land.

185 There are two important soil water deficit criteria: Soil Water Resources Use Limit by
186 Plants (SWRULP) (Guo 2010, 2014). SWRULP can be defined as the soil water
187 storage in the MID when soil water content in all soil layers within the MID equals
188 the wilting coefficient and roots can no longer withdraw water within the MID.

189 Infiltration depth is one of the most important indexes for estimating soil water deficit
190 criteria. The infiltration depth for one rain event equals the distance from the surface
191 to the crossover point between the two respective soil water distribution curves of soil
192 water with soil depth before and after the rain event (Fig. 1a). The MID will occur
193 after a continuous heavy rainfall event and a long-term cumulative infiltration process,
194 and can be determined by a series of two-curve methods (Fig. 1b). Such as in the
195 Shanghuang Ecological Experimental Station, Annual precipitation ranged from 284.3
196 mm in 1986 to 634.7 mm in 1984. For example, the MID was 290 cm, which
197 happened on 1 August 2004 after some heavy rain in August 2003– 55.0 mm on 1
198 August, 45.7 mm on 25 August and 56.4 mm on 26 August for Caragana shrub land

199 in the semiarid loess hilly region of the Loess Plateau.

200

201

202 Fig. 1. Two-curve method for estimating infiltration depth. a, infiltration depth and
203 soil water supply for one rain event. b, The maximal infiltration depth is estimated by
204 a series of two-curve methods in the soil under Caragana shrubland in the semiarid
205 loess hilly region of China. VSWC is Volumetric soil water content .

206 The root vertical distribution is another important index for estimating soil water
207 deficit criteria. For example, the majority of Caragana root biomass was distributed in
208 the 0–200 cm soil layer even though roots extended to 5.0 m, MID was 2.9 m,
209 SWRULP was 222.8 mm and LSWR was 405.7 mm in 16-year-old Caragana shrub
210 land of the semiarid loess hilly region (Fig. 2). The amount of water carried from the
211 soil through plants to the atmosphere depends on weather, plant growth and soil water
212 conditions. If the soil water supply is smaller than soil water consumption then soil
213 water resources will reduce and eventually reach the LSWR, then plants will die.

Fig. 2. The relationships among root distribution depth (RDD), wilting coefficient (WC), MID, SWRULP and LSWR in 16-year-old *Caragana* shrubland in the semiarid loess hilly region of China.

When the soil water resources in the MID equal the SWRULP, even if plants withdraw some water in soil layers deeper than the MID, the amount of root water uptake is small and will not meet the needs of plant transpiration. Therefore, this is the appropriate start time to regulate the RBP GSM. For example, the start time is the fifth year after *caragana* sowing in the degradation and receding vegetation. The amount of regulation is the difference between plant density and SWCCV, because SWCCV is the measurement of sustainable use of soil water resources by plants. When existing plant density exceeds the SWCCV and the difference between soil water supply and soil water consumption is greater than zero then soil water deficit occurs and is exacerbated with time because soil water supply is reduced (Fig. 3a) and soil water consumption increased (Fig. 3b) with increasing density in a given period. This suggests that available soil water resources will not support the existing plant population and the population should be reduced. The difference between existing plant density and SWCCV indicates the amount of regulation required.

Fig. 3. Changes in soil water supply and soil water consumption with planting density and SWCCV in Caragana shrubland of the semiarid loess hilly region, China. a, The change in soil water supply with planting density and SWCCV; b, The change in Soil water consumption with planting density and SWCCV.

4 . Soil Water Carrying Capacity for Vegetation

The idea of carrying capacity has its origin in the doctrine of Malthus (Steiguer 1995).

The term carrying capacity was first used by range managers (Price 1999) and U.S.

Department of Agriculture researchers (Young 1998) . After Raymond Pearl and

Lowell J. Reed proposed logistic equations in 1920, Odum (1953) equated the term

carrying capacity with the constant K in logistic equations (Price 1999 ; Young

1998) , see equation 1:

$$\frac{dN(t)}{dt} = rN(t)\left(\frac{K-N(t)}{K}\right) \quad t > 0 \quad (1)$$

Where N(t) is density at time t, the population per unit area at time t, r is the intrinsic

growth rate, $r > 0$ and K is an asymptote (the carrying capacity) with $K > 0$.

The concept of SWCCV

Since the 1960s, soil drought has occurred in most of the perennial grass, forest

and crop land in the Loess Plateau in China. The concepts of vegetation carrying

250 capacity, the ability of land resources to support vegetation appeared (Guo *et al* ,
251 2002) . Vegetation carrying capacity includes space vegetation carrying capacity, the
252 carrying capacity of land or space resources for vegetation, soil water carrying
253 capacity for vegetation (SWCCV) and soil nutrient carrying capacity for vegetation
254 (SNCCV). SNCCV can be subdivided into soil nitrogen or potassium or phosphorus
255 carrying capacity for vegetation and so on.

256 Vegetation includes different plant populations or communities. In nature, no plant
257 community is formed by a single plant species and form a plant populations, instead
258 many plant species live together and form the community to use space, soil water or
259 soil nutrient. Although any one species in a plant community can express SWCCV in
260 this situation in theory, but the different plant species differ in their positions and roles
261 in the community. Constructive species for natural vegetation and principal or
262 purpose species of trees or grasses are selected drought resistant plant species –
263 principal species are the main afforestation tree species and account for the majority
264 of the trees planted in a region, and purpose species of trees or grasses are those
265 cultured or managed by people in a region. Generally, principal species of trees or
266 grasses are also purpose species in a region; for example, Caragana in the Loess
267 Plateau is the regulated tree species.

268 Planting trees is a purposeful human activity to meet the need of different people;
269 Caragana is planted where vegetation is sparse and soil erosion is serious. Such plant
270 species are often exotic; sensitive to water deficits; play the most important roles in
271 preventing wind erosion, fixing sand and controlling soil , and population quantity of

272 Caragana play the most important roles in preventing wind erosion, fixing sand and
273 controlling soil and water loss in plant communities; and become the goal of
274 cultivation, management and regulation; and become the goal of cultivation,
275 management and regulation.. Thus, an indicator (plant) species is the representative of
276 a plant community to express SWCCV – either a constructive species for natural
277 vegetation, or a principal or purpose species for artificial vegetation. The SWCCV can
278 be defined as the maximum plant population quantity (absolute index) or plant density
279 (relative index) of an indicator species in a plant community when soil water
280 consumption is equal to soil water supply in the root-zone soil layers. The value of
281 SWCCV is a function of indicator species, connected with plant community type,
282 time and sites. The value of SWCCV is a function of indicator species, connected with
283 plant community type, time and sites (Guo 2014) .

284 **4 . 1 Choice of scale**

285 The choice of scale is important for calculating SWCCV. In fact, different time-scales
286 can be used to estimate SWCCV. SWCCV is meaningless on such short time-scales
287 as 24 hours or a day, and two years or more is too long. Minimum death days or
288 minimum cripple days is an appropriate time-scale to estimate soil water supply, soil
289 water consumption and then determine SWCCV, and then judge whether population
290 quantity or plant density exceeds SWCCV. Minimum lethal days is the most suitable
291 time scale.

292 Different space-scales can also be used to estimate soil water supply, such as 1 or 10
293 km² . However, a crustal block or slope is a suitable space scale to compute SWCCV

294 because there are changes in such environmental factors as radiation, precipitation,
295 wind and temperature with increasing space scale, which may change vegetation type.
296 If the space scale is too large, the environmental factors and the community type will
297 change and so influence SWCCV.

298 **4 . 2 Methods of evaluating SWCCV**

299 There are equations to estimate SWCCV, such as classic carrying capacity models
300 (Cohen 1995) , general models of population growth (Price 1999) and
301 physically-based process models (Xia and Shao 2008) and soil water–plant density
302 models ; however, soil water–plant density models are best.

303 **4 . 2 . 1 Classic SWCCV model** Classic carrying capacity models were proposed by
304 Albrecht Penck. In 1925, he stated a simple formula that has been widely used(Cohen
305 1995) . According to classic carrying capacity models, the classic SWCCV model is
306 presented in the following form:

$$307 \quad Q = \frac{C}{D} \quad (2)$$

308 Where, C is soil water resources per unit area and D is individual water requirement.
309 Ma *et al.* estimated SWCCV for eight tree species using this formula in a dry and
310 warm valley of Yunnan, China (Ma *et al* 2001) . The minimum water consumption
311 that an individual plant consumes water over a season or year when growing in a
312 normal and healthy way should be used as the individual water requirement – because
313 water consumption of an individual plant over a year changes with weather, plant
314 growth and soil water conditions. If the minimum water consumption is used as the
315 individual plant water requirement, which is suitable for saving water and precise soil

316 water management in forest and grass land even the individual water requirement

317 index, that is, the minimum water consumption is too high.

318 **4 . 2 . 2 General population growth model** This model was proposed in 1920 by

319 Pearl and Reed, who reasoned that there must be an absolute limit beyond which

320 further population growth would be impossible:

$$321 \quad N(t) = \frac{K}{(1 + e^{a - rt})} \quad (3)$$

322 Where $N(t)$, K and r are the same as equation 1; and parameters a and e are constants.

323 Given a population at different times, and at least three sets of populations and

324 relative time data, then the carrying capacity can be obtained using equation 3.

325 Because the equation has no soil water resources term , it is difficult to obtain the

326 SWCCV.

327 **4 . 2 . 3 Soil water–plant density model** If we established a set of different population

328 quantities (or densities) of indicator plants, $E_1, E_2, E_3, \dots, E_n$ at the same condition and

329 the same plot areas (e.g. 5 m × 20 m plots for Caragana in the Loess Plateau), so these

330 plots have the same radiation, temperature, annual precipitation and its distribution in

331 a season or a year, slope, slope aspect, slope position and soil type would be almost

332 the same. However, they would have differing population quantity or density and so

333 different effects on soil water supply and soil water consumption. The precipitation,

334 throughfall, runoff, plant growth, deep seepage and soil water changes with soil depth

335 and time in the root zone are measurable variables, thus the soil water supply and soil

336 water consumption for the different population quantities or densities on a growing

337 season or an annual basis can be measured, collected and statistically analysed. Soil

water supply reduces with increased planting density (Fig. 3a); and the relationship between soil water consumption and population quantity or density can be described by a parabolic equation (Fig. 3b). The quantitative relationship between soil water supply or soil water consumption and population quantity can be established using a least squares method. Generally, the soil water and plant density model can be expressed in the following form (Fig. 2):

$$F_1 = a + bE \quad (4)$$

$$F_2 = cE^2 + dE + e \quad (5)$$

Where F_1 is soil water supply, E is population quantity (or plant density), F_2 is soil water consumption and parameters a – e are constants (Guo and Shao 2004). SWCCV can be determined by combining equations 4 and 5, with the positive solution being SWCCV. During 2002 to the present, we studied Caragana shrub land planted by sowing in fish-scale pits on slopes in the semiarid Loess Plateau. For example in 2002 in 16-year-old Caragana shrub land (Guo 2014), $F_1 = 92.494 - 0.2913E$ (see Fig. 3a), $F_2 = 0.0118E^2 - 0.7575E + 64.759$ (see Fig. 3b) and SWCCV is 72 bushes per 100 m² or 7200 bushes per ha. Stem number, S , changes with plant density E , and the S and E relationship is: $S = 42.88E - 62783$, with $R^2 = 0.9632$.

4.2.4 Physically-based process model Xia and Shao proposed a process model (Xia and Shao 2008). They determined SWCCV according to the number of days that soil water content equaled the wilting point was less than the maximum number of days. This equation has many parameters and calibrating every parameter leads to error. Additionally, sclerophyllous plants such as Caragana adapt to severe dry

360 conditions through change of leaf colour and early leaf fall. The SWCCV estimated
361 by this method does not ensure that the soil water supply equals soil water
362 consumption in a growing season or a year when plant density equals SWCCV, and
363 thus this model needs to be improved.

364 Currently, the soil water and plant density model is the best model to estimate
365 SWCCV. Once a set of different density experimental plots is established, SWCCV
366 can be estimated at different tree ages and annual precipitation. The parameters a–e
367 change with time and site.

368 **4 . 3 The basic law of SWCCV**

369 The value of SWCCV changes with year because precipitation changed with year,
370 such as the precipitation in Shanghuang Ecoexperimental Station in the semiarid
371 region (Ning xia Guyuan of China) varies from 634.7 mm in 1984 to 259.9 mm,
372 which influenced the soil water supply. At the same time when trees grow, and the
373 forest canopy, annual precipitation, soil water supply and soil water consumption at
374 different population quantities or densities change on an annual basis. In 2002, the
375 relationships between soil water supply and E, and soil water consumption and E, are
376 shown in Fig. 3a and b, respectively. Combining and solving the simultaneous equations,
377 the value of SWCCV for 16-year-old Caragana was 7200 bushes per ha because Caragana
378 was clustered in fish-scale pits. The annual precipitation of 623.3 mm in 2003 was close
379 to the record maximum, and was considered as a 19-year event. Caragana is a deciduous
380 species and soil water storage at the end of the growing season exceeded that at the
381 beginning for a plant density of 8700 bushes per ha (i.e. the maximal density of the

17-year-old experimental Caragana shrub land), thus the soil water supply exceeded soil water consumption in the root zone at that time. Because there were no Caragana deaths in the plot, this suggested that the SWCCV was 8700 bushes per ha in this case. The value of SWCCV for 18-year-old Caragana was less than 1600 bushes per ha (because this was the minimal experimental density for this shrub land) in 2004 because the annual precipitation of 328.3 mm in 2004 was low, and soil water supply was less than soil water consumption in the root zone and there was no recorded Caragana death in the plot. In Caragana shrub land planted in 2002 by broadcast sowing, the SWCCV for 10-year-old Caragana was 480 000 stems per ha in 2011; in 2012, this was 420 000 stems per ha for 11-year-old Caragana; and, in 2013, 420 000 stems per ha for 12-year-old Caragana. Thus, the RBSWPG for 10–12-year-old Caragana did not require regulation because the soil water resources in the year could support the maximum experimental density, suggesting that value of the SWCCV changed with time (year) at the same site (Guo 2014) .

The value of SWCCV varies with indicator species or vegetation types at the same place during the same period. This point is supported by the study results of eight indicator trees species using the classic carrying capacity calculation formula (equation 2) in a dry and warm valley of Yunnan, China. The value of SWCCV differed across these species (Ma *et al* 2001) .

The value of SWCCV changes with location or site because soil water resources mainly come from and are closely related to precipitation(Koster *et al* 2004 ; Wang *et al* 2006) , and the annual precipitation, suitable plant species and the requirements of

economic and social development for forest and vegetation restoration differ with location. The soil water supply and evapotranspiration in forest land differ with vegetation type within the same period, so the soil water resources vary with location in water-limited regions. This is supported by four reports from China: in the Inner Mongolia Autonomous Region (Tian *et al* 2008), in Shenmu county of Shanxi (Xia and Shao , 2008) , in the Donggou Valley of Mizi (Wang and Shao 2012) and in Diedie Gully Valley in the Ningxia Hui Autonomous Region (Liu *et al* 2009, jia et al,2019) .

4 . 4 Use of SWCCV in practice

4 . 4 . 1. Fundamentals required for determining the amount of trees to be cut

The soil water resources in Caragana shrub land are reduced with increased planting density and time (forest age) under rain-fed conditions, except during wet years.

When the density of the indicator species, Caragana, exceeds its SWCCV value, soil water content under the shrub land is reduced and threatens the health and stability of the shrub vegetation ecosystem. When the soil water resources drop to the SWRULP, soil water seriously impedes plant growth(Guo 2010b). Thus, the RBPGSW needs to be regulated using SWCCV in water-limited regions. The time to start regulating the RBPGSW is at the fifth year for Caragana in the semiarid Loess Plateau (Guo and Li 2009b) .

If the population quantity or density of an indicator or purpose species of tree in a plantation exceeds the SWCCV value, the higher ecological, economic and social benefits and productivity in the plant community will be obtained at the expense of

the environment (more serious soil drying, soil degradation and vegetation decline).

Even if a soil water deficit in the plant community or forest vegetation does not immediately destroy the ecosystem, this situation will not well sustain the vegetation.

If density of the indicator species is less than the SWCCV value, the plant community does not make the most of natural resources. Thus, the present productivity, ecological, economic and social benefits of the plant community does not reflect the maximum services and benefits the rain-fed ecosystem function can provide and wastes the soil water resources.

SWCCV is the foundation to determine the amount of regulation needed. The cover degree is an important index to express the function of vegetation in reducing raindrop dynamic energy and wind velocity near the ground and conserving soil and water. The degree of cover (Fig. 4a) and productivity (Fig. 4b) in Caragana shrub land increases with planting density. Because the main erosive force is runoff in the Loess Plateau, when Caragana density exceeds the SWCCV value there is higher cover degree (Fig. 4a) and canopy interception (Fig. 5a), as well as lower runoff (Fig. 5b) and then lower soil loss (Fig. 5c). However, this is at the expense of the soil water environment because soil water consumption exceeds water supply from rainfall when planting density is more than SWCCV, which is not good for sustainable use of soil water resources and sustainable management of forest land. Keeping the planting density of Caragana at the level of SWCCV is required to balance soil water supply from rain and the plants' water requirements and make the most of soil water resources. In many cases, sustainable management of forest must be applied when the density of the indicator species in a plant

community equals SWCCV in order to avoid soil degradation and vegetation recession.

The amount of trees that should be cut when regulating equals the existing density minus the SWCCV.

4 . 4 . 2. Theoretical basis to determine criteria and indicators for sustainable forest management

Since the beginning of the 1990s, an enhanced understanding of sustainable forest management (SFM) has entered forest policy worldwide, with the concept of criteria and indicators (C&I) as one cornerstone for implementation(Wolfslehner *et al* 2005).

Over the previous decade, SFM has become a highly relevant topic in both forest and environmental policy (Sheppard and Meitner 2005) . Although much effort in SFM has focused on defining C&I for measuring sustainability (Wolfslehner and Vacik 2011) , there is no universally acknowledged method for its determination (Wolfslehner *et al* 2005 ; Sheppard and Meitner 2005 ; Wolfslehner and Vacik 2011) .

SWCCV is the foundation to determine the C & I for SFM. When the density of indicator species in a plant community equals the SWCCV value, the plant community makes the most of the soil water resources, and conditions of the community such as the appearance, crown coverage, productivity, constituents and carbon-fixing capacity should be indexes or the theoretical basis to determine C & I for sustainable management of the vegetation. The cover degree, biodiversity, productivity, biomass and its components and carbon-fixing capacity when the density of indicator species in the plant community equals the SWCCV value and the

470 requirement of stakeholders should be combined to determine C & I for SFM.

471

472

473 Fig. 4. Changes in coverage degree, prductivity and seed yield with planting density

474 and SWCCV in Caragana shrubland of the semiarid loess hilly region, China. a, The

475 change in coverage degree with planting density and SWCCV. b, The change in

476 Prductivity with planting density and SWCCV. c, The change in seed yield with

477 planting density and SWCCV.

478 This will enable maintaining and enhancing forest resources and their contribution to

479 global carbon cycles, forest ecosystem health and vitality, productive functions of forests

480 (wood and non-wood) and biological diversity in forest ecosystems because SFM depends

481 not only on natural resources' carrying capacity but also the support and input of a wide

range of stakeholders (Sheppard and Meitner 2005 ; Wolfslehner and Vacik 2011 ;
Masiero *et al*). For example, in the Loess Plateau of China, the value of SWCCV for
16-year-old Caragana is 7200 bushes per ha. When Caragana density is equal to

Fig. 5. Changes in canopy interception, runoff, soil loss with planting density and SWCCV in the Caragana shrubland in the semiarid loess hilly region of China. a, The change in canopy interception with planting density and SWCCV; b, The change in runoff with planting density and SWCCV; c, The change in soil loss with planting density and SWCCV.

The carrying capacity (i.e. 7200 bushes per ha), the cover degree (the ratio of the total area of Caragana canopies to experimental plot area or land area) of the 16-year-old Caragana is 80% (Fig. 4a), which should be the suitable vegetation restoration limit.

494 At this point, the biomass production is 1400 kg (dry weight) per ha per year (Fig. 4b),
 495 which should be the appropriate productivity, and the carbon content in the 1400 kg of
 496 biomass is the carbon-fixation capacity of Caragana. The seed yield of forest is
 497 smaller when the planting density equals SWCCV (Fig. 4c). Thus, SWCCV is the
 498 foundation to determine the C&I for sustainable Caragana shrub land management in
 499 the semiarid Loess Plateau.

500 **5 . Conclusion**

501 Rapid global economic development and increase in population in the past century
 502 has led to unprecedented consumption of natural resources to satisfy the growing
 503 demands for food, fibre, energy and water in water-limited regions. These natural
 504 assets were perceived as free and limitless for many decades. Nowadays, with
 505 scientific, technological and economic development, increasing public awareness of
 506 the value of soil, water and forest resources and the growing need for environment
 507 quality has gradually led governments to adapt their policies and strategies to match
 508 sustainability goals. This has meant dealing with the overuse of soil water resources,
 509 soil degradation and vegetation decline in the process of soil and water conservation
 510 and vegetation restoration in water-limited regions. Sustainable use of natural
 511 resources and keeping the environment sustainable in water-limited regions is the
 512 basis for sustainable development of social economy and human consensus because
 513 the area of water-limited regions accounts for the most of global land and supports a
 514 numerous and ever growing population.

515 Carrying capacity is the measure of sustainable use of natural resources. SWCCV is

516 the core issue for forest and vegetation restoration, sustainable use of soil water
517 resources, SFM and restoration of a harmonious relationship between humans and
518 nature in water-limited regions such as the Loess Plateau. We should plant trees and
519 sustainable management forests in soil and water loss regions to conserve soil and
520 water and improve the environment. In water-limited regions, soil water resources are
521 reduced with growth of forest even with a sudden increases of soil water resources
522 after rain events. When the soil water resources equal the SWRULP, soil water
523 severely constrains plant growth. When this occurs, SWCCV should be estimated –
524 on which the RBPGSW can be regulated.

525 SWCCV is the ability of soil water resources to support vegetation and can be defined
526 as the maximum plant population quantity (absolute index) or plant density (relative
527 index) of indicator (plant) species in a plant community when soil water consumption
528 is equal to soil water supply in the root zone on an annual basis in a water-limited
529 region. The value of the SWCCV is a function of plant community (indicated by
530 indicator species), time (expressed in years) and location. When the density of
531 indicator species in a plant community is more than the SWCCV value, the RBSWPG
532 should be regulated .When the density of indicator species in a plant community
533 equals the SWCCV value, the conditions of the community such as the appearance,
534 crown coverage, productivity and its constituents and carbon-fixing capacity should
535 be indexes or the theoretical basis to determine C&I for sustainable management of
536 forest and vegetation and sustainable produce of crop. The SWRULP and SWCCV
537 provide a scientific basis for sustainable use of soil water resources in the process of

538 vegetation restoration and determining C&I for SFM in water-limited regions.

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