The eco-water requirement for forest restoration and research requirements for northern China

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BACKGROUND

Environment problems

In the northern regions of China there are four major environment problems related to water and forest vegetation.

First, is the very low forest coverage — for example, only 0.79% for Xinjiang, 1.54% for Ningxia and 4.33% for Gansu province — because precipitation is too low and through historical deforestation.

Second, is the very low precipitation in most parts of north-western China where it is only around 200–400 mm, for example, 276 mm in Ningxia, 236 mm in Gansu and 112 mm in Xinjiang. Precipitation varies greatly, both seasonally and yearly. In general, precipitation from June to September accounts for around 80% of yearly total. The annual runoff is only about 10–50 mm in the northern regions. The water resource thus available amounts to only 19% of the total of the whole of China, while the corresponding ratio of land area is 63%. Furthermore, the uneven distribution of precipitation often leads to severe drought and floods, and makes the use of water resources more difficult.

Third, is the severe soil erosion as a result of less vegetation and high rain intensity. For example, the soil erosion modulus in the Loess Plateau, where the erosion is the highest, amounts to 5000–10 000 t km^{-2} a^{-1} and with some extremes between 20000–40000 t km^{-2} a^{-1}.

The fourth is the fast increasing desertification. According to monitoring results by China's State Forestry Administration in 1999, the desert areas are still expanding at an average rate of about 10 400 km^2 a^{-1}; China has 2.674 million km^2 of desert land, accounting for 27.9 % of the total territory and mainly distributed in the northern regions.

Forest/vegetation restoration

Much research in forest hydrology has been carried out in China, and the hydrological benefits of forest vegetation have been well realised, for example, by increasing soil infiltration, reducing soil erosion (Wang, 1986; Zhang and Liang, 1996), decreasing the amount and velocity of surface runoff, minimising soil evaporation (Sun and Zhu, 1995), lowering the flood peak discharge (Liu and Huang, 2003) and stabilising river runoff between rainy and dry seasons.

Although many environment problems in the northern regions are highly interrelated, increasing forest coverage is commonly believed to be helpful to solve or minimise most of the environment problems. Restoring the forest coverage was decided by the government to be the most important and urgent task for improving the environment in the northern regions in the coming years. Therefore, large-scale forestry programmes have been started since 2000, such as 'natural forests protection', 'return slope farmland into forests'. According to the Chinese State Administration of Forestry plan, more than 7 million ha of farmland will be returned to forest before 2010 in the northern regions. The forest coverage will thus be increased from 10.38% in 2000 to 14.77% in 2050.

LIMITATION OF SOIL WATER

Over the last few decades, China has been making great efforts to restore or increase afforestation in the northern regions. However, in many cases it did not succeed; the limitation of soil water capacity to support the planted trees is thought to be an important reason.

Dried soil layer

A dried soil layer was observed first in the 1960s, but not much attention was paid to it at that time. It was only in the 1980s, as a cumulative result of afforestation and vegetation restoration, that a dried soil layer began to be widely observed in artificial forest/vegetation in the northern regions.

A dried soil layer is defined as the long-term continuous and critical deficit of soil water in the depth range affected by root systems because there is more water consumption than water input. He *et al.* (2003) defined the dried soil layer as that where the soil water varies from wilting point to 60% of field capacity, i.e. from 8% to 14% of water content by weight, since 60% of the field capacity is thought to be the natural stable water content in the Loess Plateau.

A dried soil layer exists not only in the arid and semi-arid region but also in the semi-humid region (Yang, 1996). In arid region, the dried soil layer began to be formed immediately after planting shrubs. In the semi-arid zone, soil drying-up was observed in the young stands of trees aged only a few years. In the semi-humid region, the dried soil layer was observed both in the planted forests and in the secondary forests, but it deeper, mostly below 1–2m. However, the dried soil layer is mainly reported for sites with deep soil, such as in the dune areas and in the Loess Plateau, but less in the stony mountain areas with thin soil.

The dried soil layer is not limited to forests which generally have a higher transpiration, it exists also with shrubs and grassland, or even in high-yield cropland. The degree and depth of the drying soil layer are influenced by vegetation type (forest, shrub, grass). The drying effect of forest is generally higher than shrub and grass. In Guyuan, Ningxia, where the annual precipitation amounts to 480 mm, a soil water deficit appears even from the second year after planting the erect milkvetch (*Astragalus adsurgens* Pall.). The soil water in the 1–3m depth decreased to near the wilting point when erect milkvetch is 5–6 years old, and the soil water in whole profile decreased to near wilting point in the seventh year.

The degree of soil drying depends on the balance between water input and water consumption. After comparing the reported researches in the Loess Plateau, Hou *et al.* (1999) found that both the degree and depth of the dried soil layer vary with annual precipitation. In semi-humid region, the depth of soil recharged by infiltrated precipitation is 1–3 m and thus the dried soil layer begins generally from 2 m below the soil surface. The corresponding depth in the semi-arid region is about 1–1.5 m. For specific annual precipitation volumes, soil drying is a function of slope, slope aspect, slope position, vegetation type and vegetation biomass, which influence the soil water balance (He *et al.* 2003).

Until now, severe dried soil layers were observed mostly in the plantation forest. The main reasons may include many factors but unsuitable design of plant communities is thought to be the most important one. A dried soil layer is not a conseqwence of vegetation restoration, but is a result of vegetation establishment with communities composed of more water-consuming introduced species and/or at a higher density compared with the native plant communities.

Stability of vegetation

Soil drying leads to soil degradation in the form of increasing salt concentration in soil water and increasing soil compactness. Plants growing on sites with a dried soil layer show reduced growth and earlier death. For example, the yearly height increment of poplar growing on sites with a dried soil layer can be only 5–20 cm, which is only 10–25% of normal trees. The life of planted erect milkvetch communities varies between 3–8 years, depending on the drought stress.

The soil degradation caused by soil drying makes natural regeneration worse and more difficult replanting. For example, there is virtually no young Chinese pine and poplar on the floor in the sites with severe soil drying. The survival rate of planted *Hippophae rhamnoides* in May (one month after planting) was 80% on a slope with soil water content of 11.5%, while it was only 15% on a slope with soil water content of 4% in May and 0% in June (Hou *et al.*, 1999).

The restored forest vegetation in a large area in the northern regions is and will be influenced by the drought stress and soil drying. It seems to be an important factor influencing the stability of the newly established forest vegetation. How to design, establish and manage the forest communities in these regions based on water balance should be a new challenge both for research and practice.

Soil water carrying capacity of vegetation

Since the vegetation restored for environmental improvement may live for many years and the annual variation in precipitation is very large, keeping the soil water balance at a relatively higher level for most years is a fundamental precondition for a stable and successful vegetation restoration. Therefore, the soil water carrying capacity for vegetation should be based on the long-term soil water balance. Guo and Shao (2003) expressed the soil water carrying capacity as the tree density, under which the soil water consumption is not excessive and the soil water is recharged by infiltrated precipitation. However, water consumption is very different among plant species, and plant density cannot be widely used as a simple indicatior among different plant types and species.

After realising the water deficit problem in dune-fixation forests, Cui (1998) suggested establishing dune-fixation forest at a lower density and using native plant species. Based on a five-year study of the water balance in protective forest in the southern part of Loess Plateau, Yu and Chan (1996) concluded that the soil water there can support a normal growth of black locust plantation for the first 10–16 years and for 5–8 years for Chinese pine. In contrast to the trees, the soil water can support the normal growth of shrubs. Zhu *et al.* (2002) suggested arranging the protective forest system based on water balance, but this design arrangement is not related directly with the possible dynamic soil water situation.

To improve the soil water condition for individual trees, Wang *et al*. (2002) designed a rainwater harvesting system for afforestation in Loess Plateau. It is successful for promoting the growth of young trees but cannot also meet the need of water yield from the catchment, and a water deficit will appear again as the trees grow.

Evaluating the water balance is one of the ways to design and manage the restored forest vegetation in a sustainable way. This principle is now well understood and widely accepted in China. Liu and Liao (1999) have estimated the proper forest area ratio of 33.1% based on water balance in Chifeng, Inner Mongolia. It was found that the previously planned forest area ratio of 42.35% is too high and should be reduced. However, a lot of research is still required to quantitatively estimate the dynamic soil water carrying capacity and the water consumption of vegetation. Furthermore, the water yield function of catchments should not be neglected in calculating the soil water carrying capacity and the design of the vegetation community.

ECO-WATER AND WATER USE ARRANGEMENT

The sustainable development in a region with limited water resources must be based on optimal allocation of water for different aspects, for example, agricultural irrigation, industry, water for drinking, base flow of rivers and forest vegetation. However, because of lack of knowledge of how best to balance water use with environmental protection, eco-water has been neglected for a long time. On other hand, the possible effect reducing the water yield from catchments by increasing forest vegetation has also been neglected. This leads to many conflicts for water uses. Nowadays, the question of how to establish efficient arrangements for water use to ensure both economic and ecological sustainability, is attracting more and more attention.

Water use conflict

Because increased forest vegetation consumes more water, a reduced ground water level after vegetation restoration was observed in many sandy areas. In the Loess Plateau, a more forested catchment produces less annual runoff than the much less forested catchment (Yang *et al.* 1994; Huang and Liu, 2002; Liu and Huang, 2003). For the same ground cover ratio by forest canopy or grass, less runoff was produced in the small forested catchment than that covered by grass (Huang *et al.*, 1999). Increasing forest vegetation consumption of limited water will enhance the conflict of water uses.

On other hand, forests in the oasis systems in the northern regions were widely and strongly damaged or decreased by reduced river water input and groundwater levels. This is mainly caused by increased agricultural irrigation in oases and in the headwaters. For example, the area of forest and shrub in the Ejina oasis (Liu and Zhang, 2002) and along the Tarimu river (Cao *et al.*, 2003) has decreased dramatically within the last 30 years. The remaining vegetation is not healthy because of drought stress. Allocating a certain amount of eco-water in regional water use plan is very urgent and necessary for saving the forest vegetation in oasis systems (Jiao *et al.*, 2001).

Definition of eco-water

The eco-water oriented research in China began simply from the calculation of water consumption for maintaining forest vegetation in oasis ecosystems. By analysing the water resources problem and oasis construction, Tang (1995) put forward the concept of eco-water, but this was not defined clearly. Jia and Xu (1998) defined eco-water as the water used by ecosystems to maintain or improve the ecological balance; it was thus classified but applicable to oasis ecosystems only.

Eco-water can be considered on two levels. In the general or broad sense, it is the indispensable water used for maintaining, stabilising and harmonising the global ecosystem (Zhang *et al.*, 2001), or for maintaining the water balance of global bio-geo-ecosystem (CAE, 2000; Shen, 2001). In the narrow sense, it is the gross water (including surface and groundwater) used by all vegetation types in terrestrial ecosystems for environmental protection and improvement (CAE, 2000; Shen, 2001). Chen and Wang (2001) suggested that eco-water is the water needed for maintaining or improving the balance of plant communities, animals and non-biological components of the environment.

Liu *et al.* (2001) differentiated between the required eco-water and consumed eco-water. The former is the maximum water consumption of vegetation at its potential production under conditions of unlimited water supply and soil fertility. The later is the real water amount used by vegetation in actual conditions and it is influenced by climate, vegetation and soil water.

In conclusion, most researchers adopt the conception of eco-water in the broad sense, but some difference exists in the narrow sense. All considered vegetative eco-water as a key, large and more difficult component. Clearer definitions, more detailed classification and more accurate estimation are needed.

Calculation of vegetative eco-water

Until now, most estimations of eco-water were concentrated in the arid zone for oasis ecosystems, with calculations based on the vegetation type, area and eco-water quota. The quota is influenced by climate, vegetation and soil water conditions. In the northern regions of China, there are many different vegetation types, classified into natural and artificial vegetation, and divided into forest, forest steppe, steppe, meadow, desert steppe and desert, according to the main component. The forest can be further differentiated according to the main tree species. The vegetation pattern and water condition are very different from region to region, from site to site, from season to season, and these variations must be taken into consideration when calculating the eco-water in a region.

When estimating the eco-water in Xinjiang, Jia and Ci (2000) classified the vegetation into oasis plantation, riverine forests, desert forest/shrubs, floodplain meadows, etc. Within the oasis plantation, it is further divided into shelterbelt forest, timber forest, fuel wood and orchards. The eco-water quota for each vegetation type (and tree species) in each region was estimated.

The water consumed by vegetation includes the uncontrollable precipitation, the controllable surface water and groundwater, also the soil water which is between controllable and uncontrollable. However, most eco-water studies were static and did not consider the soil water, especially for studies in the arid zone. However, in some studies the uncontrollable precipitation is considered during the eco-water estimation. By calculating the eco-water in north-west China using remote sensing and GIS, Wang *et al.* (2002a, b) estimated the precipitation consumption quota of each vegetation type in different regions. Zhang and Yang (2002) also took precipitation and soil water as components of water cycling into account in estimating eco-water.

The area of vegetation is an important factor influencing regional eco-water amount. In most studies, only the area where more water than precipitation is needed for vegetation is included (Jia and Ci, 2000). The area where the vegetation can survive on precipitation is not included, such as the mountain forest. This implies that the forest vegetation in the mountain area is optimal and will not be changed, or that vegetation restoration will not influence the total runoff. But in fact this is not this case. It was suggested that the forest vegetation restored in the mountain area within the Yellow River Basin should be included in the eco-water estimation (CAE, 2000; Wang, 2000) because they have an influence on the regional water resource. However, the forest/vegetation in the mountain area in the arid zone, the timber forest and shelterbelt in northern China were not included in the eco-water estimation.

By estimating the eco-water demand in north-western (Wang, 2000) and northern regions (CAE, 2000), the eco-water quota of different vegetation types was estimated according to the water consuming characteristics of typical vegetation in different regions and the actual amount of available soil water, or according to the amount of runoff reduced by different vegetation. The eco-water quota of forest in mountain area is 15 mm a^{-1} in the Yellow River basin, 30 mm a^{-1} in the Hai River basin, and 0 mm a^{-1} in the arid zone. The eco-water of shelterbelt is 100 mm a^{-1} on the plain of the Yellow River basin with annual precipitation of more than 400 mm, and 320 mm a^{-1} in the oasis system of the arid zone. The eco-water quota is 5 mm a^{-1} for the artificial grassland on the Loess Plateau. However, there is still big differences among the different estimations, for example, the eco-water quota estimated by Jia and Ci (2000) in Xinjiang is much higher. It seems that detailed hydrological researches are needed to derive a more reasonable estimation of eco-water.

FURTHER RESEARCH NEED

Much progress has been made in the research on eco-water, however, many gaps or weaknesses still exist. It seems that eco-water will be a new focus in future researches, both for hydrology, water and catchment management, forestry and ecology in the arid, semiarid and semi-humid regions. The research to be done urgently is as follows:

(1) Further development of widely applicable definitions and calculation procedures for eco-water;
(2) Eco-water estimation based on the soil water dynamics, plant physiology, and forest/vegetation stability;
(3) Design and management of optimal vegetation community structure for different protection purposes, based on soil water balance;
(4) Development of an eco-hydrological model to understand the interrelationship between forest vegetation and water, and to couple the hydrological and ecological processes;
(5) Variation of eco-water quota during the succession/restoration of degraded vegetation, relating eco-water quota with vegetation structure and water condition;
(6) More field experiments at different temporal and spatial scales for determining more exactly the eco-water quota of typical vegetation and plant species in different regions;
(7) Application of GIS, RS and up-scaling techniques for more consideration of the spatial and temporal heterogeneity of vegetation and water conditions;
(8) Optimal eco-water allocation in regional water resource use plans based on scenario analysis of ecological and ecological benefits;
(9) Balance among the multi benefits of forest vegetation, such as water yield, soil protection, flood control, water retention, sand fixing, water quality improving, crop protection etc.

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