AN ECOHYDROLOGICAL ANALYSIS FOR OPTIMAL USE OF REDISTRIBUTED WATER AMONG VEGETATION PATCHES

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Abstract. Ecosystem processes in semiarid landscape mosaics are strongly affected by the interactions among water utilization, plant growth, and vegetation patterns. Management of these semiarid landscapes can be improved with better understanding of the complex interactions between ecology and hydrology that determine the water-use efficiency at landscape and regional scales. However, quantifying the effects of runoff and applying ecohydrological principles toward the improvement of land-use management requires additional research to integrate the ecological and hydrological processes. This study highlights the importance of runoff in the management of vegetation to retard desertification by reducing soil erosion. By coupling a plant growth model with a simple GIS-based model of water redistribution and use, we analyzed the interactions among runoff generation, “runon” reabsorption, and plant growth, in a small watershed in the semiarid sandy grassland area of northern China. Net primary productivity (NPP) and water utilization for the watershed were calculated for different managerial schemes. Annual aboveground NPP (NPPa), maximum leaf biomass (Mleafmax), and water use simulated with runoff effects were 18%, 21%, and 8% greater, respectively, than those simulated without runoff redistribution. Furthermore, simulation with a proposed management strategy for sandy grassland landscapes, which prescribes different plant functional types (grasses, shrubs, and trees) distributed at different slope positions, led to increasing NPPa, Mleafmax, and water use by 34%, 8%, and 28%, respectively, compared to the current land use. The increases in NPP and biomass in turn would reduce wind erosion and associated dust-storm generation and enhance capacity of the system to retard degradation. The coupled model thus can be used as a tool to quantify effects of runoff redistribution for optimal land management and environmental protection, and the study has important managerial implications for semiarid systems, where degradation is of major concern, and runoff redistribution is important.

Key words: ecohydrology; land-use management; net primary productivity; Ordos Plateau, northern China; rainfall redistribution; runoff and vegetation management; sandy grasslands; sandstorm; semiarid landscape; water-use efficiency.

INTRODUCTION

Semiarid landscapes occupy about 35% of the global landmass, and most have been experiencing degradation due to high sensitivity and vulnerability to climate change and human disturbances (Millennium Ecosystem Assessment 2005, Wilcox and Newman 2005). For example, the prolonged chronic ecological degradation of the semiarid landscapes in China has recently been exacerbated by the heavy burden of a huge population and booming economic development (Ci 1997). This expedites soil erosion, land degradation, and desertification (Sneath 1998), and causes severe environmental problems that affect not only the local and surrounding areas (Lim and Chun 2006, Shao and Dong 2006, Xu et al. 2006), but potentially the entire globe as well (Husar et al. 2001).

Much of northern China including Beijing is experiencing progressively severe sand storms generated in the semiarid grasslands and deserts, and the dust emitted from these areas has reached the North American continent (McKendry et al. 2001, Tratt et al. 2001). The most severe event, which occurred 16–17 April 2006, was estimated to load the municipal area of Beijing with 336,000 metric tons of dust, 0.3–1.0 mm in depth and 20 g/m², in one night (Liu et al. 2006, Han et al. 2007). These ecological and environmental problems may escalate in the near future due to climate change and expected intensification of anthropogenic disturbances (Yang et al. 2004).

Because of the increasing intensities and extents of regional environmental problems, degradation of semiarid lands is a top concern for many governments and scientists. In China the government is investing in a substantial effort to design and implement nationwide,
large-scale ecological restoration programs in arid and semiarid areas to retard desertification (CCICCD 1995, 1997, Ci 1997). However, some of these efforts have failed to achieve their goals. For example, the Three-North Windbreak Project (TNWBP) was supposed to build a protective forest shelterbelt running from the northeast to the northwest of China in the 1980s. But trees in many sections of the TNWBP, especially those in the sandy grassland areas in the Ordos Plateau (Fig. 1), either died—apparently due to water stress—or grew only to a dwarf state, providing little protection against wind erosion. These results suggest that accurate estimations of long-term water availability, an ecohydrological issue focusing on interactions between vegetation growth and hydrological processes, are needed to develop effective management strategies.

Recent research suggests that collection of runoff occurs more extensively than previously appreciated and is biologically important (Zalewski 2000, Wilcox et al. 2003, 2005, Hannah et al. 2004, Caylor et al. 2005, Huxman et al. 2005, Pataki et al. 2005, Scanlon et al. 2005, Seyfried et al. 2005, Wilcox and Newman 2005). Consequently, at arid or semiarid sites with mean annual rainfall between 200 and 400 mm, vegetation growth may depend not only on the amount of vertical rainfall but also on the amount of water redistributed laterally by surface runoff/runon (inflow runoff) and by subsurface drainage. Depending on the patterns of vegetation, topography, and parent material, in some locations the laterally transported water can be much more important than the vertical rainfall (Aguiar and Sala 1999). Furthermore, runoff could be one of the major drivers for vegetation patterns in semiarid landscapes. As a water concentrator, it gives rise to spatially heterogeneous vegetation distributions, with vegetation patches acting as runoff acceptors and interpatch openings as donors. In places with inadequate average rainfall supply to support any vegetation, the positive feedback between vegetation growth and runoff interception contributes to greater production than would be expected for spatially homogeneous sites without runoff-mediated water concentration (Aguiar and Sala 1999).

The principles of arid-land ecohydrology have been conceptually formulated in the trigger–transfer–reserve–pulse (TTRP) model by Ludwig et al. (2005). However, the quantification of runoff and its effects in assessing land-use managerial practices remains understudied. The difficulties lie in an inadequate quantitative understanding of the interactions between rainfall redistribution (runoff or runon [lateral flow, both overland and subsurface, into a vegetation patch; i.e., inflow runoff]) and plant growth, and the absence of appropriate methodologies for practitioners (Gao 1997, Wilcox and Newman 2005, Newman et al. 2006, Gao et al. 2007).

Quantitative ecohydrological analyses are extremely important for improving land-use management in semiarid areas, where degradation is of concern, and water redistribution is important. One promising area for application is the hilly Maowusu sandy grasslands of the Ordos Plateau in the warm temperate zone of northern China. With rainfall concentrated in July and August, this area is characterized by poor soil water retention, patchy vegetation distribution, low soil fertility, low primary productivity, and severe soil erosion by water and wind. Large amounts of water redistributed by surface runoff and subsurface drainage are quite often partly due to the hilly landscape and poor water retention of the sandy soils (Li 1990, Zhang 1994, Gao et al. 1997).

How should vegetation be managed to maximize water-use efficiency and primary productivity with the aims of reducing wind erosion and retarding desertification? To quantify the spatial distribution of plant water availability at landscape scales, Gao (1997) developed a simple hydrological model, which accounts for runoff-driven rainfall redistribution but not for interactions between runoff and vegetation. More practically, Zhang (1994) proposed a revegetation scheme with repeating grass–shrub–tree bands lined up perpendicular to the slope of a site. However, quantitative justification of the design using a model built upon ecohydrological principles still does not exist.

Quantification of the effects of runoff redistribution and the application of ecohydrological principles to improve land-use design are pivotal in filling the knowledge gap between conceptual models and land-use practices. In this paper we analyze the water use and vegetation production of a watershed in the Maowusu sandy grassland, based on the interactions between rainfall redistribution and plant growth, using a patch-scale vegetation-growth model coupled with a runoff-transfer–reabsorption model. With the same model, we tested the hypothetical grass–shrub–tree revegetation design using computer simulation. We discuss how our results, which highlight the importance of runoff redistribution in management practices, will advance our knowledge of ecohydrological processes and consequences in land-use management, and improve efforts for optimal land use to deter land degradation. The present study has important managerial implications not only for northern China, but across semiarid systems.

**Study Area and Methods**

**Study area description**

The Maowusu sandy grasslands are located in the Ordos Plateau of northern China with a total area of 32,000 km². Sandy soils, hilly landscapes, and concentrated summer rainfall are the most important characteristics of the area (Li 1990, Zhang 1994, Gao 1997, Gao et al. 1997, 2002). The 34-km Kaokaowusu River is located in the northeast of the Maowusu sandy region with a watershed that occupies 482.8 km², at 39°16′12″–39°36′ N and 109°43′12″–110°8′24″ E, and 1131–1490 m above sea level. The mean annual temperature is 7°C,
and the average annual precipitation is 370 mm. The mean annual potential evapotranspiration is 2370 mm, over 6 times the annual rainfall (data from Chinese Meteorological Administration, available online).  

Soil types of the watershed were classified based on soil development and chemical and physical characteristics of soil profiles (Xiong and Li 1987). Sand dune soil is the dominant soil type, occupying 67% of the area. Skeletol soil and Castanozem occupy 19% and 3% of the watershed, respectively. Fluvo-aquic soil is found in lowland and riparian areas, covering about 5% of the watershed. Meadow aeolian soil is only sparsely distributed in this area. Grasslands cover 72% of the watershed. Woodlands (mostly plantations) and shrublands dominated by peashrub occupy 12% and 2% of the watershed, respectively. Rain-fed cropland (mostly millet) is the main agricultural type and occupies 6% of the watershed. Irrigated cropland (mostly corn) and barren land occupy only 0.4% and 1% of the landscape, respectively (Fig. 1, data reconstructed from Gao et al. [2002]). Consequently, the plant functional types of the watershed are trees, shrubs, grasses, irrigated crops, and rain-fed crops. The representative species are Simon poplar (Populus simonii Carr.) for trees, intermediate peashrub (Caragana intermedia Kuang et. H.C.Fu) for shrubs, needlegrass (Stipa breviflora Griseb.) for grasses, maize (Zea mays L.) for irrigated crops, and broomcorn millet (Panicum miliaceum L.) for rain-fed crops.

**Patch vegetation growth model**

The “terrestrial ecosystem simulator” (TESim) is a suite of process-based models used to simulate water, carbon, and nitrogen dynamics in plants and soils at the patch, landscape, and regional scales (Gao and Zhang 1997, Gao and Yu 1998, Yu et al. 2002a, Gao et al. 2007). We used the patch-scale version of TESim (TESim-P) for our plant growth model (Appendix A). Briefly, the model calculates plant carbon assimilation using leaf models for C_3 and C_4 species developed by Thornley and Johnson (1990) with modifications by Gao et al. (2004). Leaf carbon assimilation is scaled up to the canopy level by considering light attenuation caused by leaf shading from the top to the bottom of the canopy. Net primary productivity (NPP) is calculated as net canopy assimilation minus the respiration of roots and stems. The allocation of carbon and nitrogen among plant pools is controlled by plant phenology, leaf water potential, and whole-plant nitrogen deficit. Vertical water flux is driven by precipitation events, surface evaporation, transpiration, soil water potential gradient, and hydraulic redistribution by roots (Zou et al. 2005). Runoff is generated when daily rainfall fills soil water to the field capacity of a specific penetrating depth (Gao and Reynolds 2003). TESim does not use infiltration excess, which is commonly used for instantaneous runoff calculations (temporal resolution of minutes) and relatively important for soils with low hydraulic conductivity. For sandy soils and with daily time-step models such as TESim, field capacity excess (FCE) has proved to be a reasonable strategy (Kemp et al. 1997, Gao and Reynolds 2003). By calculating runoff as FCE, horizontal drainage (subsurface flow) becomes a part of runoff flow, given that there is often hardpan below the root zone. Litter decomposition, nitrogen mineralization, and soil respiration are simulated as in the CENTURY model (Parton et al. 1987, 1988), however the passive soil organic-matter pool is not simulated. We used the
decomposition function developed by Lomander et al. (1998a, b). Symbiotic nitrogen fixation is calculated according to Kemp et al. (2003) and Yu et al. (2002b). The model was parameterized and validated for different plant functional types (PFT) and soil types with field data of hourly leaf photosynthesis, daily soil water, seasonal plant growth and biomass (Gao et al. 2007).

Application of TESim-P coupled with a hydrological model to the Kaokaowusu watershed

To analyze the interactions between rainfall redistribution and plant growth, and to evaluate the water balance of the Kaokaowusu watershed, we first used the TESim-P model to simulate plant growth under different levels of water availability. Data from the literature were used for parameterization of soil texture, nutrient levels (Zhu et al. 1994, Zhang 1998), and plant biomass (Liu et al. 1993, Xing and Liu 1993). Daily weather records of the Yijinhuoou station (39°34′12″ N, 109°43′48″ E) from 1976 to 1994, which covers a climate shift from cooling to warming in northern China (Gao et al. 2007), were used to drive the model.

The model was run preliminarily for 19 years to approximate equilibrium values for soil carbon and nitrogen, litter mass, and live plant biomass, for all soil type–PFT combinations. The end values of state variables of the preliminary run were then used as the initial conditions for the final simulation runs. We estimated the baseline average water use, NPP, and maximum leaf biomass of the watershed for each soil type–PFT combination under current rainfall, without considering interactions between rainfall redistribution and plant growth. Runoff, defined as overland and subsurface flows in this study, was assumed to approximately equal precipitation minus water use, because percolation to groundwater in this region is small (Zhang 1994, Gao 1997, Gao and Zhang 1997). Runon is defined as lateral flow, both overland and subsurface, into a vegetation patch (in short: inflow runoff).

To simulate different runon inputs, we set up a series of 18 scenarios with discrete mean annual runon (or runon) values ranging from 0 to 1060 mm. These 18 discrete scenarios are hereafter named P0, P1, ..., P17. For each scenario, runoff events have exactly the same timing as rainfall events from weather records, and the size of each runoff event equals the size of the corresponding rainfall event multiplied by the ratio of Pi (i from 0 to 17) to the mean annual precipitation (MAP) during the period. Simulations were run for each soil type–PFT–runon combination. The average annual NPP, maximum leaf biomass, and evapotranspiration (referred to hereafter as water use) across the simulation period were assumed to represent typical plant growth states and water-use conditions under the corresponding water supply (rainfall + runon) levels.

To investigate the effects of spatial redistribution of water and highlight the importance of runoff, we used a digital elevation model (DEM) with a resolution of 74 × 74 m and with data from the U.S. Geological Survey (available online) to create a map of flow direction using the hydrological module of ArcGIS (ESRI 2002). Soil type and land-use maps of the watershed produced by the local government (Gao et al. 2002) were converted to the same resolution as the DEM.

To analyze the interactions between rainfall redistribution and plant growth, we assumed that all runoff from a grid cell was available to the next adjacent grid cell in the downslope direction. This assumption was based on observations of runoff redistribution in hilly areas with small slopes similar to those that were the focus of this study (Fig. 1c, 99.95% of the watershed has slopes <15°). Most runoff in sandy soils is in the form of subsurface flow rather than rapid overland flow. Therefore, the available water (Wi) for each grid cell included current precipitation plus runoff from the upper grid cells. The water use and plant growth for each grid cell were calculated by driving the vegetation growth model (TESim-P) with the corresponding water availability (Appendix B). To simplify calculation, we assumed that

\[
\begin{align*}
\text{NPP}(W_a, &\text{PFT, Soil}) = \text{NPP}(P_i, \text{PFT, Soil}) \\
\text{Mleafmax}(W_a, &\text{PFT, Soil}) = \text{Mleafmax}(P_i, \text{PFT, Soil}) \\
\text{WaterUse}(W_a, &\text{PFT, Soil}) = \text{WaterUse}(P_i, \text{PFT, Soil}) \\
\end{align*}
\]

where \(P_i \leq W_a < P_{i+1}, \text{ for } i = 0 \text{ to } 16, \text{ and} \)

\[
\begin{align*}
\text{NPP}(W_a, &\text{PFT, Soil}) = \text{NPP}(P_{17}, \text{PFT, Soil}) \\
\text{Mleafmax}(W_a, &\text{PFT, Soil}) = \text{Mleafmax}(P_{17}, \text{PFT, Soil}) \\
\text{WaterUse}(W_a, &\text{PFT, Soil}) = \text{WaterUse}(P_{17}, \text{PFT, Soil}) \\
\end{align*}
\]

where \(W_a \geq P_{17} \) when \(W_a \) is the available water (vertical rainfall + runon); \(P_i \) is the \(i\)-th level of water availability, \(i \) from 0 to 17; PFT and Soil indicate the plant functional type and soil type, respectively; Mleafmax is the annual maximum leaf biomass; and WaterUse is the evapotranspiration. The detailed calculations are based on an iterative procedure in ArcGIS to delineate available water distribution (Fig. 2).

Analysis for a proposed land-use change

The objective of the grass–shrub–tree (GST) land-use design by Zhang (1994) for small slopes (>5° but <25°) was to optimize vegetation production and other ecosystem functions (such as reducing wind erosion), under limited rainfall conditions, by maximizing the use of redistributed water. In this design, grasses are used to increase total vegetation cover, while trees and shrubs are planted to capture redistributed water and protect against wind erosion. About one third of the upper unit in this design is left bare to yield runoff. Mixed grass–

\(6 \) (http://edcsns17.cr.usgs.gov/srtmbil/)
Shrub vegetation is planted in the middle of the unit with one to two rows of shrubs upslope and downslope and a row of grasses in between. Mixed grass–tree vegetation is planted at the lowest location with one row of trees at the slope bottom (Fig. 3a). Experiments showed that shrubs and trees within the GST managerial unit could grow well by efficiently utilizing the runoff and also serve as windbreaks to reduce erosion (Zhang 1994, Zheng and Zhang 1998). Compared to a former protective forest design implemented 20 years ago, under which trees either died of water stress or did not reach mature heights, the GST design is much more effective.

To apply the GST managerial unit to the watershed of interest and account for the associated spatial heterogeneity, we evaluated the average response of a GST unit to different soil types and water availability. The size for each GST unit was set to be $74 \times 74$ m in order to match the resolution of existing landscape map layers. To characterize the uneven water use and water distribution within each GST unit, we subdivided each GST unit into sub-grids with $1 \times 1$ m resolution. The fine grid of the GST unit was then subjected to the same ecohydrological analysis outlined above, again for different soil types and amounts of available water (Fig. 3b). The only difference between this fine-scale analysis and the previous coarse-scale analysis was that we assumed runoff from an upper-slope grid cell was available for a variable number of grid cells downslope. Flow length, defined as the maximum reachable downslope distance of runoff, depends on slope and soil hydraulic conductivity. However, quantitative information on flow length is still lacking for this area. We therefore performed a sensitivity analysis of GST productivity and water use...
with variable flow lengths (1, 10, 20, 30, 40, and 50 m), and used the means to represent the GST responses to soil type and water availability.

The criteria for implementing GST units are (1) the GST units will be planted in areas with slopes >5°, and (2) the GST units are used only when they increase both aboveground NPP and maximum leaf biomass. The ecohydrological analysis was repeated with the implementation of GST units to obtain distributions of annual NPP, maximum leaf biomass, and water use of the watershed, and the results were compared with those based on the current land use.

**RESULTS**

**Responses of plant growth to increased water availability at the patch scale**

The greatest enhancements in annual NPP (net primary productivity), maximum leaf biomass, and water use resulting from increased water availability due to runoff were observed for trees relative to other plant functional types (Appendix C). Even for trees on sand-dune soils with low nutrients and water retention, the annual aboveground NPP (NPP\(_{a}\)) was 232%, maximum leaf biomass was 234%, and water use was 181% of those values with current rainfall amounts, when water availability was increased to 380% of the current level. Plants grew the best on fluvo-aquic soils and the poorest on sand-dune soils. The growth of rain-fed crops on sand dune soils was the lowest; the annual NPP\(_{a}\) under the current rainfall was only 8%, 11%, 14%, and 16% of rain-fed crops on fluvo-aquic soils, castanozems, meadow aeolian soils, and skeletol soils, respectively.

**Water use and NPP of the watershed under the current land-use pattern**

Across the watershed, the mean annual NPP\(_{a}\) was 137 g m\(^{-2}\) yr\(^{-1}\), maximum leaf biomass was 68 g m\(^{-2}\), and annual water use was 153 mm/yr, when runoff reabsorption was not considered. The watershed mean annual NPP\(_{a}\) increased to 161 g m\(^{-2}\) yr\(^{-1}\), maximum leaf biomass to 82 g m\(^{-2}\), and annual water use to 165 mm/yr, when runoff reuse was considered by coupling the vegetation-growth model with the topographic hydrological model. Consequently, the effects of runoff reuse gave rise to increases of 18%, 21%, and 8% on average for NPP\(_{a}\), maximum leaf biomass, and water use, respectively (Fig. 4a).

**Water use and NPP with GST managerial design**

Not surprisingly, the simulations based on different flow lengths indicated that water use of the grass–shrub–tree (GST) managerial unit was the greatest under the 1-m flow-length assumption, and the lowest under the 50-m assumption. At the current rainfall, water use under the 50-m flow length decreased by 5–8% for the five soil types compared to those under the 1-m flow length. Differences in water use between 1-m and 50-m flow lengths decreased with increasing water availability.

The annual NPP\(_{a}\) and maximum leaf biomass of the GST unit were greater than those of the grassland for any of the five soil types. Values for the GST units were also higher than those of the rain-fed cropland for sand-dune soils.
Accordingly, the land-use pattern was adjusted to implement GST units as follows. For areas with slopes >5° degrees (88% covered by grasslands), all grasslands were converted to GST units, and the rain-fed croplands on sand-dune soils were also converted to GST units. Other areas remained unchanged. The annual NPP\textsubscript{a}, Mleafmax, and water use of the watershed with the implementation of GST units were then simulated considering the interactions between rainfall redistribution and plant growth (Fig. 4b).

In areas with slopes >5° degrees, the mean annual NPP\textsubscript{a} increased from 104 g m\textsuperscript{-2} yr\textsuperscript{-1} under the unaltered land use to 129 g m\textsuperscript{-2} yr\textsuperscript{-1} under the adjusted GST land-use design. Mleafmax increased from 51 to 65 g/m\textsuperscript{2}, and water use increased from 92 to 112 mm/yr. For areas converted to the GST managerial unit, the average annual NPP\textsubscript{a} increased from 79 to 106 g m\textsuperscript{-2} yr\textsuperscript{-1}, Mleafmax increased from 40 to 55 g/m\textsuperscript{2}, and water use increased from 80 to 102 mm/yr (Fig. 4c).

**Fig. 4.** The annual water use (cm), aboveground NPP (NPP\textsubscript{a}), and maximum leaf biomass (Mleafmax) of the watershed under (a) the current land-use pattern and (b) the adjusted land-use pattern with GST (grass–shrub–tree) design, and (c) comparisons between the current and the GST-adjusted land-use patterns for areas with slopes >5° or on areas changed to the GST unit.
Our results illustrate that vegetation, water, and nutrients are closely coupled (Ludwig et al. 2005, Newman et al. 2006), and land-use management affects both ecological and hydrological processes as well as their interactions. Poor water retention by sandy soils can result in subsurface horizontal flow on slopes, even within the rooting zone. On the other hand, the dry surface of sandy soil helps to prevent water loss via surface evaporation. Our simulations estimated that the average annual surface evaporation rate from a bare sand-dune soil for the period from 1976 to 1994 was 44 mm/yr, similar to the experimental results by Kobayashi et al. (1992), who reported that surface evaporation from sandy soils in Maowusu was <10% of the annual rainfall (~370 mm) during the period from April to October.

Rooting patterns clearly differ among plant functional types (Jackson et al. 1996), and changes in soil water availability may have different effects on shallow- and deep-rooted plants. In this modeling study, trees were much more sensitive to increasing water availability than were shrubs, grasses, irrigated crops, and rain-fed crops. These results are consistent with the following assumptions/observations. (1) Trees have a much deeper root profile than the other plant functional types in the simulation, and thus they are less affected by the water content of the shallow soil layers and surface evaporation, but more influenced by variations in rainfall that alter deeper soil water content; (2) water retention of the sandy soils is very poor, with a field capacity calculated from soil texture of 10% (volumetric); (3) irrigated crops were watered and thus not sensitive to increases in precipitation; and (4) the increase in water availability was only in the form of increased size for each rainfall-runon (lateral flow, both overland and subsurface, into a vegetation patch) event, but without altering the frequency of the rainfall-runon events. The increase in available water for each event (precipitation plus runon) would mostly benefit deep-rooted plants. For shallow-rooted plants, increases in rainfall frequency might be more beneficial (Grover and Musick 1990).

Although water plays a key role in semiarid systems, “nutrient availability, which is intimately linked to water, may exert a strong or even codominant influence to limit the response of vegetation to soil moisture” (Newman et al. 2006:4). Poor nutrient content was another feature of the sandy soils in this area, which co-affected the ecosystem production. In our study, shrubs, represented by intermediate peashrub, was the only plant functional type with the ability to fix nitrogen and was less affected by the nutrient limitations of the soil. The response of shrubs to soil moisture in our simulations might therefore be greater than that of other plant functional types, which are more limited by poor nutrient availability. As an example, we found that in the baseline scenario (P0), the aboveground net primary productivity (NPPa) of shrubs growing on castanozem (with greater water retention and soil moisture compared to meadow aeolian soil) was 3.0 times that of shrubs growing on meadow aeolian soil, whereas NPPa of grasses on castanozem was only 1.7 times that on meadow aeolian soil, and NPPa of trees growing on castanozem was only 1.2 times that on meadow aeolian soil.

The importance of runoff has been noted in recent research on semiarid ecosystems (Belnap et al. 2005, Huxman et al. 2005, Ludwig et al. 2005, Wilcox and Newman 2005, Wilcox et al. 2005). Our study highlights the importance of accounting for key ecohydrological relationships—redistribution of runoff in this case—within watersheds so that land can be managed more efficiently (Newman et al. 2006). Previous research has indicated that, without additional runon, a mean annual rainfall of 400 mm can hardly provide sufficient water for trees in the Maowusu region (Zhang 1994). However, due to their strong sensitivity to water availability, the trees could possibly grow well in patches where accumulation of runon substantially increased water availability. When redistribution of runoff was considered in our ecohydrological analysis, NPP and maximum leaf biomass for a typical watershed in this sandy grassland area increased by 18% and 21%, respectively, compared to that estimated without considering runoff redistribution.

Not only does the present study develop a feasible methodology for coupling ecosystem hydrological processes, but it also provides an effective case study for improving silvicultural design in semiarid sandy regions. The design of a repeating pattern of the grass–shrub–tree (GST) combination (Fig. 3) takes advantage of different plant functional types by coordinating them in a way to make use of redistributed water. The comparison of water use and production of the watershed between the current and the GST-adjusted land use indicates that the latter substantially enhanced water-use efficiency and ecosystem production. In addition, because slopes are susceptible to water erosion, the increased NPP and biomass of areas with slopes >5° degrees (using the GST design) may increase ecosystem capacity to conserve water and to retard erosion by water.

Plant leaf biomass, which can serve as an indicator of both ecosystem production and protection against wind erosion, was increased by 38% in the GST-adjusted areas (Fig. 4c). Hence the GST land-use design has the potential to enhance environmental protection by substantially reducing wind erosion and associated local desertification, as well as the probability of sandstorm generation.

The lateral movement of nutrients with runoff flow may reduce the nutrients in upper slopes and increase them downhill. This potential spatial redistribution of nutrient availability by runoff has not yet been included in this study. Various natural and human disturbances, such as livestock grazing and fire, have also not yet been
considered. Further integrative research on hydrology, water-mediated nutrient flow, vegetation growth, and various disturbances, will improve the capacity of process-based models to predict the land-use management impacts on ecohydrological processes (Newman et al. 2006).

In summary, we developed an ecohydrological method that couples a patch-scale vegetation growth model and a GIS-based hydrological model to analyze water use and carbon assimilation of a sandy grassland watershed in northern China. Subsequent simulations tested the feasibility and advantages of a newly proposed land-use scheme with grass–shrub–tree combinations. Our approach, to take into account runoff and its redistribution and re-absorption, advanced our quantitative understanding of the complex interactions between ecological and hydrological processes at landscape scales, and provided a land-use management scheme that takes advantage of different plant functional types for controlling desertification and reducing severe sandstorms in this region. The methodology is applicable to most arid and semi-arid sandy systems where land-degradation issues are of major concern and runoff redistribution is also likely to be important.

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APPENDIX A

A schematic representation of the structure of the TESim-P model (Ecological Archives A018-057-A1).

APPENDIX B

A simplified chart for ecohydrological analysis along a slope (Ecological Archives A018-057-A2).

APPENDIX C

The responses of the annual aboveground NPP of trees, shrubs, grasses, and rain-fed crops on five soil types to increasing water-availability levels (Ecological Archives A018-057-A3).