ECOLOGY AND SOCIETY

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The following is the established format for referencing this article:
Rockström, J., L. Gordon, C. Folke, M. Falkenmark, and M. Engwall. 1999. Linkages among water vapor flows, food production, and terrestrial ecosystem services. Conservation Ecology **3**(2): 5. [online] URL: http://www.consecol.org/vol3/iss2/art5/

Research

Linkages Among Water Vapor Flows, Food Production, and Terrestrial Ecosystem Services

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ABSTRACT

Global freshwater assessments have not addressed the linkages among water vapor flows, agricultural food production, and terrestrial ecosystem services. We perform the first bottom-up estimate of continental water vapor flows, subdivided into the major terrestrial biomes, and arrive at a total continental water vapor flow of 70,000 km^3/yr (ranging from 56,000 to 84,000 km^3/yr). Of this flow, 90% is attributed to forests, including woodlands (40,000 km^3/yr), wetlands (1400 km^3/yr), grasslands (15,100 km^3/yr), and croplands (6800 km^3/yr). These terrestrial biomes sustain society with essential welfare-supporting ecosystem services, including food production. By analyzing the freshwater requirements of an increasing demand for food in the year 2025, we discover a critical trade-off between flows of water vapor for food production and for other welfare-supporting ecosystem services. To reduce the risk of unintentional welfare losses, this trade-off must become embedded in intentional ecohydrological landscape management.

KEY WORDS: catchment management, ecohydrological landscape, evapotranspiration, food production, freshwater management, global freshwater assessment, resilience, terrestrial ecosystem services, trade-offs, water use efficiency, water vapor flows.

Published August 6, 1999.

INTRODUCTION

Earth is a human-dominated planet. The well-being of humanity is intimately dependent upon the ecological life-support systems now undergoing rapid changes (Vitousek et al. 1986, Lubchenco 1998). The capacity of ecological systems to continuously supply a flow of nature's services to humanity is largely taken for granted (de Groot 1992, Daily 1997), despite the fact that this capacity is increasingly becoming a limiting factor for socioeconomic development (Odum 1989, Folke 1991, Jansson et al. 1994).

In many areas, both locally and regionally, available freshwater is already a limiting factor for industrial development, household needs, and irrigation of crops (Gleick 1993, Falkenmark 1997). An estimated 25% of the world's food market is at present driven by water scarcity, i.e., food is imported due to insufficient irrigation water for local food production (Postel 1998). A recent analysis indicates that 55% of the world population in 2025 will live in countries incapable of self-sufficient food production, due to lack of water for irrigated agriculture (Falkenmark 1997). Furthermore, water quality deterioration caused by human activities is diminishing the quantity of freshwater available to society (Lundqvist 1998). Recent estimates indicate that humanity appropriates for industry, households, and irrigated agriculture 54% of the global accessible runoff flow (Postel et al. 1996).

However, freshwater - the bloodstream of the biosphere - is also needed to drive critical processes and functions in forests, woodlands, wetlands, grasslands, croplands, and other terrestrial systems, and to maintain them resilient to change. These systems generate numerous essential ecosystem services, including biomass production in agriculture and forestry (Costanza et al. 1997). Surprisingly, past international global freshwater assessments of whether or not humanity is heading toward regional and even a global water crisis, have neglected the water vapor flows supporting the generation of ecosystem services (Gleick 1993, UN-SEI 1997). Generally, it is only the liquid runoff water, moving across the continents in rivers and as groundwater flow, that is perceived as the freshwater resource for socioeconomic development. Even if there is reason to be concerned over future liquid water use, by far the largest proportion of terrestrial production of food, biomass, and the generation of other ecosystem services originates from rain-fed land use. As an example, around two-thirds of the world's food, harvested from 83% of the world's croplands, is derived from rain-fed production (Gleick 1993).

In this article, we perform the first bottom-up calculation of continental water vapor flows. The estimate is generalized from field studies of water vapor flows from different biomes, focusing in particular on croplands, grasslands, forests, woodlands, and wetlands, biomes of great significance for the generation of terrestrial ecosystem services. The estimate includes calculations of a range of water requirements for terrestrial biomes, depending on water management and annual climatic variations.

We begin to address the complex, but largely neglected, issue of the interplay among water vapor flows, agricultural food production, and the generation of ecosystem services in terrestrial biomes. Our findings highlight the fact that the critical issue of how to feed a growing human population through agricultural food production cannot be tackled in isolation from the freshwater-dependent generation of ecosystem services in the surrounding landscape.

INVISIBLE GREEN WATER VAPOR AND VISIBLE BLUE LIQUID WATER

In the *Introduction,* we distinguished between water vapor flows and liquid water flows. In the literature on water and food production, water vapor and liquid water are sometimes called green water and blue water, respectively

(Falkenmark 1995). Both concepts provide useful tools for the analysis of local, regional, and global flows in the hydrologic cycle. Liquid (blue) water flow is the total runoff originating from the partitioning of precipitation at the land surface (forming surface runoff) and the partitioning of soil water (forming groundwater recharge) (Fig. 1). Water vapor (green) is the return flow of water to the atmosphere as evapotranspiration (ET), which includes transpiration by vegetation and evaporation from soil, lakes, and water intercepted by canopy surfaces (Rockström 1997). We regard ET as the result of the work of the whole ecosystem, including the resilience it needs for securing the generation of ecosystem services in the long run.

Previous estimates, e.g., L'vovich and White (1990), have calculated ET indirectly as the difference between precipitation, *P*, over continents (110,305 km^3/yr) and total runoff, *R*, (38,230 km^3/yr), arriving at 72,075 km^3/yr. It should, however, be noted that in areas where data on rainfall and river flow did not exist, the estimates were done using the six component model developed by L'vovich (1979), in which runoff is estimated from regression curves related to rainfall, and the partitioning between drainage and evapotranspiration is through proportionality curves specific for different biomes.

ESTIMATING WATER VAPOR FLOWS OF MAJOR TERRESTRIAL BIOMES

The distribution of ecosystems on a global scale is, to a large extent, governed by climatic factors including water availability, but it can also be influenced by natural or human-induced disturbance regimes. When water is in free supply, the ET from a complete green canopy of standard crop can be predicted directly from climatic factors (Thornwaite and Mather 1955, Penman 1963). This is called *potential ET.* The *actual ET* of an ecosystem, however, is dependent on (1) the water supply, limited by the amount of precipitation, on-flow of water, and ability to store water in the system; and (2) the processes in an ecosystem that modify the amount of water flowing in and out from the system. These processes, necessary for the generation of ecosystem services, include the development of deep or shallow rooting structures, transformation of topography, and changes in size of leaf area, and they are largely dependent on the quality of the soil. The ET of an ecosystem is thus not only a factor of climate but also a result of the ability of the biota to modify the available water flow.

We based our calculations on spatial coverage, multiplied by annual ET (in millimeters peryear) of each system, and subdivided them as far as possible according to ecosystem properties influencing ET, i.e., primarily vegetation cover and climate (Table 1).

For croplands, a somewhat different method was used, because they are located in a wide range of climatic regions (from tropic to boreal and from arid to humid), vary highly in production intensities, and there are detailed data on production (yield x surface area) and water requirements of production. By crop production, we refer to actual harvest and not to potential crop production. Biomass production in croplands is roughly linearly proportional to ET for constant hydroclimatic conditions, when water is not limiting growth (Sinclair et al. 1984). The slope of the relationship between biomass growth and ET is defined as the water use efficiency (WUE). WUE has, however, been defined in various ways in the literature, commonly as the amount of transpired water per yield unit, or the amount of water applied (through irrigation) per yield unit.

We have used this relationship in the calculation of water vapor flow from croplands, multiplying the annual crop production (in megagrams per year of harvested economic biomass; 1 Mg = 1 ton) by WUE estimates (cubic meters per megagram). The WUE data for each subgroup in Table 1 derive from a broad number of sources (*n* in Table 1; fully specified in Appendix 1).

The actual water vapor flow for each subsystem will vary in space and over time, due to climatic fluctuations, different biotic and abiotic conditions, and different land management practices. We have taken into account the effects of such variations on water vapor flows by calculating a high and low estimate for each subgroup, based on the lowest and the highest ET or WUE data.

Grasslands, wetlands, woodlands, and forests

Surface extensions of the biomes shown in Table 1 were derived from those in *Carbon in Live Vegetation of Major World Ecosystems* (Olson et al. 1983), except for wetlands, for which we used Matthews' (1983) *Global Database on Distribution, Characteristics, and Methane Emission of Natural Wetlands.*

Grasslands include all noncultivated formations with <10% tree canopy cover, thus including natural grazing land, pastures, and shrubland. Woodland is a wide description, with various densities of trees and tree canopy coverage between 10% and 99%. Forests are defined by tree canopy coverage of 100% (Olson et al. 1983). Wetlands include bogs/fens and swamps/marshes, and are here defined as permanently or seasonally inundated areas, forested or nonforested.

Based on the subclasses from Olson et al. (1983), some reclassifications were made (Table 1). In wetlands and forests/woodlands, vegetation type and climate interact in the generation of ET (Mitch and Gosselink 1983, Nulsen et al. 1986); these biomes were thus classified in subgroups according to those variables. For grasslands, we have assumed that total ET depends primarily on climatic factors rather than on vegetation cover, although the relation between evaporation and transpiration can vary (Penning de Vries and Djitèye 1982, Liang et al. 1989). For warm and hot grasslands with annual precipitation of $P < 600$ mm/yr, we assume that ET = *P* (i.e., that there is no liquid water flow). This assumption is valid for dry grasslands on a large spatial scale (le Hourerou 1984). For grassland systems with P > 600 mm/yr, 20% runoff is assumed. The ET data for each subgroup derive from a broad number of peer-reviewed sources (indicated under *n* in Table 1 and fully specified in Appendix 2).

Croplands

Agricultural ET was estimated from mean crop production data over a period of five years (1992 -1996) using individual crop data from FAO (Faostat 1997). The time span was included to reduce the effects of interannual yield fluctuations.

WUE data were collected for each major food crop. All crops were classified into 16 subgroups according to key parameters influencing WUE, i.e., hydroclimate, plant community, and the harvested part of plant (grain, fiber, fruit, etc.). Special attention was given to ensure that the WUE values corresponded to the economic yield registered in Faostat. WUE data from several research sites were included for each major crop and subgroup in order to reflect the variability in ET for different agricultural settings (see Appendix 1).

These calculations for croplands cover ET requirements to produce the harvested economic yield. Added to this flow is the ET water from other non-economic vegetation in agricultural lands. Here, non-economic vegetation includes weeds and vegetation in open drainage ditches, green enclosures, and wind breaks. This vegetation can, however, support ecological services in that it can, for example, contribute to nutrient retention in the landscape and provide a habitat for insects that may be important for pollination and predation of pests (Matson et al. 1997). Earlier efforts at estimating this share of the water cycle are very rudimentary. For example, the total net primary production (NPP) in croplands used in Postel et al. (1996) and Postel (1998), and based on Vitousek et al. (1986) and Ajtay et al. (1979), includes only NPP from crops grown for harvest. The assumption that the total annual ET, based on this NPP multiplied with a global average WUE, would reflect the actual ET from the world's croplands seems to be a very rough estimate. We have not found any global estimate of NPP in croplands coming from weeds, drains, ditches, etc., nor an estimate that covers the ET from this production. Thus, we assume that 10% of the average annual rainfall over land surfaces (834 mm/yr), i.e., roughly 80 mm/yr, supports non-economic biomass growth in agricultural lands. Even though our estimate, based on the assumption that 10% of the precipitation on croplands supports such production, is crude, it seems more reasonable than previous estimates.

Results of water vapor estimates of major terrestrial biomes

The estimate resulted in a total water vapor flow from forests, woodlands, wetlands, grasslands, and croplands of 63,200 km^3/yr (Table 2). We estimated the total water vapor flow from grasslands to be 15,100 km^3/yr (range 9300 to 21,700 km^3/yr); from forests and woodlands to be 40,000 km^3/yr (range 35,300 - 45,000 km^3/yr); and from wetlands to be1400 km^3/yr (range of 1100 - 1700 km^3/yr) (Table 1). The total water vapor flow in the world's croplands for crop production was estimated as 5400 km^3/yr, with low/high values ranging from 3600 to 8400 km^3/yr. Adding ET for non-economic plant growth on agricultural lands of 1300 km^3/yr gives a mean water vapor flow of 6700 km^3/yr, ranging from 4900 to 9800 km^3/yr.

We believe our estimates to be conservative, especially for agriculture. Our ET estimates for crop production only relate to harvested yield after reduction for threshing and post-harvest losses (which can amount to > 20% of the ET-demanding crop on the farmer's field). The WUE data used in this article originate from research stations that generally have more favorable cultivation conditions than does the farmer, which results in higher WUE values than under on-farm conditions. Our data show that, on average, some 1400 m^3 of ET flow is needed to produce 1 Mg of cereal grain in the tropics. There are, however, many research findings suggesting that WUE is much lower in farmers' fields, often amounting to some 3000 - 6000 m^3/Mg (Dancette 1983, Rockström et al. 1998). This is explained by relatively lower soil fertility, higher runoff losses, and less advanced land management practices on-farm, and will result in lower yields (< 1000 kg/ha in sub-Saharan Africa) and higher soil evaporation losses. This low WUE in agriculture is reflected by the high estimate in Table 1 of 8427 km^3/yr for crops.

The aggregate estimate in Table 1 ranges from 49,000 to 77,000 km^3/yr, which is roughly a deviation of 14,000 km^3/yr from the mean. The large fluctuations in water vapor flow within the subgroups mainly reflect four different sources of variation: location, climatic fluctuations, land management, and random error. It is worth mentioning that the fluctuation of annual rainfall over land surfaces is of the same order of magnitude as our estimated water vapor fluctuations, and varies between 90,000 and 120,000 km^3/yr. The considerable variations in water vapor use suggest that mean water vapor estimates, especially for agriculture, are of limited interest in assessing regional and global freshwater needs. The range includes parameters that we cannot influence (e.g., soil properties and hydroclimatic fluctuations), but also factors that we can influence through integrated land and freshwater management.

The large range also indicates that there is an important potential for improving WUE in agriculture. Crop management, such as choice of cultivars, planting density, crop protection, and soil and water management, will affect the ratio between ET and yield and, thereby, WUE. In soil and water management, care must be taken with nutrients and soil structure in order to minimize the effects of erosion and runoff. Variations in WUE for a specific crop species also illustrate the capacity of a certain crop to grow in a spectrum of hydroclimates (e.g., maize from humid to semiarid tropics).

Postel et al. (1996) estimated the freshwater requirements for the annual human appropriation of net primary production of grasslands to be 5800 km^3/yr, and of harvested forest products to be 6800 km^3/yr. Postel (1998) also estimated the annual human appropriation for total food production (including croplands, grazing lands, irrigation water losses, and aquaculture) to be 13,800 km^3/yr.

In summary, earlier estimates suggest that humans depend on some 14,900-15,800 km^3/yr (Table 2) of water vapor to support human-appropriated primary production. This corresponds to 21-22% of the top-down estimate by L'vovich and White (1990) of water vapor flow from continents (72,075 km^3/yr). Our results indicate that the major terrestrial biomes appropriate as much as 88% of this water vapor flow.

ESTIMATING TOTAL WATER VAPOR FLOWS FROM CONTINENTS

As shown in Table 2, our estimated average water vapor flow from croplands, forests, woodlands, grasslands, and wetlands amounts to 63,200 km^3/yr. By adding water vapor flows from remaining continental systems, we perform, to our knowledge, the first bottom-up calculation of total water vapor flows from continents. The estimate is generalized from field studies of water vapor flows from different biomes.

Evapotranspiration from green areas in urban settlements has been estimated at 100 km^3/yr (Postel et al. 1996), and vapor flows from lakes account for an estimated 600 km^3/yr (L'vovich 1979). Added to this is the complex grey zone of domestic water use by rural societies. The magnitude of this *upstream rural water* evaporating after use is difficult to estimate. If 82% of the population in developing countries (estimated from WRI 1994 and FAO 1995) is assumed to have a daily need, for domestic purposes, of 150 l p/d, an estimated 180 km^3/yr is appropriated. The suggested domestic daily water use of 150 l p/d is taken as an aggregate of Shuval's estimate of roughly 25 m^3 p^{-1} yr^{-1} (= 68 l p^{-1} d^{-1}) needed for basic small-scale production of legumes, livestock, and chicken around homesteads in arid regions (Lundqvist and Gleick 1997), and Gleick's suggested basic household need of water amounting to 50 l p/d (Gleick 1996). 20 l p/d were added in order to reflect the water demand for animals in pastoral communities and large-scale livestock raising.

L'vovich and White (1990) estimated that the volume of water in small reservoirs amounts to some 5% of the volume in large reservoirs (about 5500 km^3 when full). Based on this, we have estimated the vapor flow from small reservoirs as 30 km^3/yr, by assuming an average depth of small reservoirs to 3 m and a vapor flow of 400 mm/yr. In Table 2, we include the vapor flow from small reservoirs in upstream rural water use. Large reservoirs (with a storage capacity > 100 x 10^6 m^3) return an estimated 130 km^3/yr of vapor flow to the atmosphere (L'vovich and White 1990).

Tundra and deserts, covering some 31 x 10^6 km^2 of land (Olson et al. 1983), with an average annual ET of 180 mm (Frank and Inouye 1994), return approximately 5730 km^3 water to the atmosphere each year. These biomes play a role in global climate and support local human populations and biota.

Adding evaporation from lakes, large and small reservoirs, and ET flow from green areas in human settlements, tundra, and deserts, and upstream rural water use gives a total water vapor flow of about 70,000 km^3/yr (Table 2). This implies that our estimate generalized from field data of water vapor flows from a diversity of systems has captured 97% of previous global top-down and indirect ET estimates from continents. It should be noted, however, that this range might vary between 56,000 and 84,000 km^3/yr (51-76% of annual mean rainfall) just by taking into account the variation of the major biomes (Table 1).

How much of this freshwater flow does humanity depend upon for terrestrial ecosystem services? Because ecosystems are complex systems linked dynamically across spatial and temporal scales, it is difficult to judge human water vapor dependence on a global level. There are those who believe that such a dependence should only be attributed to a particular service or to marginal changes in freshwater requirements between services and other human uses of freshwater. There are others who would argue that the water vapor requirement of the whole ecosystem is necessary for the generation of ecosystem services, at least in a longer term and sustainability perspective. In the following section, we will discuss interrelations between freshwater and terrestrial ecosystem services, and illuminate the many welfare-supporting ecosystem services that depend on complex ecosystem dynamics, which, in turn, depend on the bloodstream of the biosphere.

INTERRELATIONS BETWEEN WATER VAPOR FLOWS AND TERRESTRIAL ECOSYSTEM SERVICES

Physical and chemical processes provided by freshwater are fundamental. Water constitutes an essential building block in all terrestrial production, contributes to the processes that generate ecosystem services, and provides crucial interconnections within and between ecosystems. It works as a carrier of solutes, plays a key role in global, regional, and local climate regulation, and sets the ecohydrological conditions for biological diversity in any habitat.

Freshwater availability is a prerequisite in the *production* (e.g., crops, timber, cattle), *information* (e.g., nature experiences, aesthetic information), and *regulation* (e.g., formation of topsoil, sequestering of CO_2, assimilation of nutrients) functions of the environment (de Groot 1992). These functions are defined as ecosystem services and include ecological processes that produce, directly or indirectly, goods and services from which humans benefit (Daily 1997).

Crops, trees, cattle, and other biomass production depend on accessible renewable freshwater. Nature requires water for food web support to wildlife and for maintenance of habitats in which they live. The processes of topsoil formation in forests and croplands and nutrient retention in wetlands involve water. Grassland systems develop patchy dynamics that respond to water availability by redistributing water and nutrients in the landscape for improved performance (Walker 1993). Ecosystem services of tropical rain forests depend both on water transpired by vegetation and on evaporation that supports species adapted to a moist environment.

Ecosystems are interconnected by liquid water and water vapor flows. Forests are linked to other systems such as grasslands and wetlands, both directly and indirectly, in ways in which freshwater plays a critical role. Freshwater directly transports mineral nutrients and organic matter between systems. Indirectly, freshwater supports services across ecosystems, such as the spreading of seeds, both directly by water and indirectly as water is needed to sustain a habitat for mobile organisms that spread seeds, and to sustain a habitat for bees and other insects that are important for pollination. The biota play an important role in the regulation of atmospheric water by redirecting liquid water to water vapor flow, thereby recycling it to local rainfall. This can be of great significance, e.g., in the Sahel region where > 90% of the rainfall appears to be attributed to ET flow from vegetated land surfaces (Savenije 1995). Furthermore, terrestrial ecosystems contribute to freshwater quality through biochemical processes such as denitrification and other forms of microbiological activity, and by facilitating infiltration, thereby moderating river flow seasonality, erosion, and flooding.

Freshwater is also required for ecosystem resilience. Resilience is the buffer capacity to disturbance performed by functional groups of species linked in complex temporal and spatial webs of interactions (Peterson et al. 1998). Dynamics of ecosystems (Holling 1986) and variability in water flow patterns can interact and respond to each other with feedback mechanisms at different temporal and spatial scales (Mitch and Gosselink 1983, Swank et al. 1988). Forest fires can cause huge runoff increases that may impact on downstream systems, as experienced in Australia (E. O'Laughlin, Canberra, Australia, *personal communication*). Resilience makes it possible for a forest to absorb a fire and maintain the potential to reorganize and recover, thereby continuing to supply ecosystem services essential to society, and also to reduce negative effects on downstream water-ecosystem services for other human uses. Similarly, grasslands have adapted to disturbances such as invasion of grazers or insects, fire, and periods of flooding or drought, and need the dynamic interactions of biological diversity to respond in a resilient fashion to these disturbances (Walker 1993). Freshwater is a key driverin these dynamics.

Putting freshwater in such an ecological context and in the light of data in Tables 1 and 2 suggests that the degrees of freedom for production of life support for the expanding world population is limited. There will be fundamental trade-offs between food production and other welfare-supporting ecosystem services in terms of available freshwater.

FRESHWATER, FOOD, AND ECOSYSTEM SERVICES FOR A GROWING HUMAN POPULATION

The per capita dependence on water vapor for production of food in croplands is roughly 1180 m^3/yr, based on a population of 5.7 billion people in 1995 (UN 1997). Recognizing that the human population probably will reach 6 billion within the next few months, we used data from 1995, as they can be compared with the data on crop production that we have used, which refer to the years 1992-1996. Future demand for food will involve an increased appropriation in terms of additional water vapor flow for crop production. (Grasslands also provide food in terms of animal protein. However, because grazing is only one of multiple functions in the grassland system, and is also a process within the system, it would be misleading to try to estimate how much of the 2650 m^3 p^{-1} yr^{-1} of water vapor estimated here from grasslands is attributed to cattle production).

L'vovich and White (1990) have estimated the changes in runoff during the past 300 years (1680-1980) caused by redirections of liquid water to water vapor flows through irrigation. Their results suggest that the water vapor flows have increased from 86 km^3/yr to 2570 km^3/yr during this period. In the coming 100 years, they estimate a further doubling in response to food production needs. Considerable changes in water vapor and liquid water flow patterns seem unavoidable.

Using the human population increase reported by the United Nations (UN 1997), i.e., an increase of 2.6 to 8.3 billion in 2025, and assuming a current per capita water vapor use for crop production, we calculate an additional water need of 3100 km^3/yr in 2025. This would imply a total crop water demand in 2025 of about 9,800 km^3/yr, a 31% increase in

3100 km^3/yr in 2025. This would imply a total crop water demand in 2025 of about 9,800 km^3/yr, a 31% increase in freshwater demand for crop production. Could we appropriate this amount of freshwater in a trade-off-free manner toward other terrestrial biomes? We have identified three possible options.

The first option, propagated by international organizations (e.g., FAO, UNDP, IIMI), is to increase irrigated agriculture. According to Shiklomanov (1997), the increase in ET in irrigated agriculture by 2025 would amount to 425 km^3/yr, or about 14% of the additional freshwater demand. Because increased irrigation implies *liquid-to-vapor redirection* of freshwater and, thereby, a continuation of river depletion, the scope for solving future food shortages through irrigation alone, without causing severe impacts elsewhere, seems limited (Leah 1995).

The second option is to improve rain-fed agriculture (Falkenmark et al. 1998). There seem to be two major avenues. The first is to improve water-use-efficiency in crop production by *redirecting in-field evaporation to transpiration* within croplands, i.e., increasing the yields with the same amount of water vapor flow. It seems reasonable to assume a 10% overall increase in WUE as a result of e.g., better crop varieties, improved farming practices, soil fertility management, and soil and water conservation measures. This would diminish the future water needs by about 300 km^3/yr. The second avenue is to *redirect evaporating surface runoff for use in croplands.* This option concerns water that now runs off from croplands and evaporates in areas of low biomass productivity and degraded lands, predominantly in semiarid and arid regions, i.e., water that never reaches rivers and does not contribute to the generation of ecosystem services. This water could be captured by surface-water harvesting and used for supplementary irrigation during dry spells (Rockström and Valentin 1997). This measure would not only conserve water but alsowould conserve soil by diminishing erosion caused by surface water runoff. A first-cut estimate of this option is arrived at by a comparison between surface runoff on a local scale from croplands vs. runoff on a continental scale, assuming an even distribution of croplands globally. The amount of water available for redirection from *evaporating surface runoff* in semiarid and arid regions for use in croplands is hard to estimate. We assumed that the difference in surface runoff coefficients between field scale and continental scale for croplands in Africa, Asia, and South America is attributed to *evaporating surface runoff.* An even distribution of croplands on the different continents was assumed. Croplands cover 10.5% of the global terrestrial area. The runoff water from croplands available for surface water harvesting in Africa, Asia, and South America would then be roughly 300 km^3/yr. See Appendix 3 for data and references.

Thus, it may very well be that developments in irrigated and rain-fed agriculture cannot cover the full need of increased water appropriation for food production, actually only about one-third or 1000 km^3/yr out of 3100 km^3/yr, according to our first-cut estimate. Desalinization of seawater for food production is not a viable solution because the costs would be several factors higher than the price of the crops.

It seems as though the final option to feed another 2.6 billion world inhabitants until AD 2025, is to *redirect substantial amounts of water vapor flows from other biomes to croplands.* Intensifying the conversions of forests, woodlands, and, to some extent, grasslands and wetlands, to croplands in the tropics and subtropics is a likely development scenario. Assuming that the main part of the remaining freshwater demand would be appropriated from tropical/subtropical systems, their water vapor flows would decrease by 5.5% in only 25 years. Because most of the population growth will occur in the tropical region, this is also where the increase in food production primarily will occur. Thus, we divided the 2100 km^3/yr of additional water vapor needed by the total water vapor from our estimates in tropical grasslands, forests, woodlands, and wetlands, which amounts to 38,000 km^3/yr, thus resulting in a 5.5% increase.

There is a severe risk that further land use change to capture freshwater for crop production will lead to increasingly fragile, less diverse systems with lower resilience, and will cause subsequent *erosion of ecosystem services.* Will such redirections of water vapor increase or decrease total human well-being? The results of our estimate, in the light of an expanding human population and escalating globalization, illustrate that we are facing major challenges in freshwater-land use management. Management must explicitly deal with what we call the increasing *water vapor-related scarcity.* This "new scarcity," which concerns the critical trade-off between water vapor for ecosystem services generated by terrestrial biomes and water vapor for food production, has not been sufficiently addressed in freshwater assessments.

INTENTIONAL ECOHYDROLOGICAL LANDSCAPE MANAGEMENT

The critical trade-off between use of water vapor for food production to a growing world population or for welfare-supporting ecosystem services must be addressed in a conscious way. Proper attention must be paid to side effects generated by land use change. Modifications of ecosystems will alter water flows, and redirection of water flows will modify ecosystem services. There are numerous intentional local and sector-based land use decisions that have caused unintentional ecologically and water-driven side effects. Such effects are generally discussed under the term "environmental impacts," without perception of the causes behind them.

Ecologically driven side effects of land use conversion, such as shifts in key functional groups of species or loss of resilience, can change ecological and hydrological preconditions for the generation of ecosystem services. For example, movements of organisms in the landscape may change, and thereby impact on ecosystem services such as pest control, pollination, and seed dispersal by birds, bats, mammals, and insects (Baskin 1997, Bisonette 1997).

Ecologically driven side effects can impact on processes of significance to the surrounding region (such as denitrification by wetlands), or processes performed on a local scale, but valued at a global scale (such as sequestration of CO_2 by forests). These side effects may accumulate and transfer to the landscape and further, to a regional and even to a global scale (Holling 1994).

Freshwater-driven side effects of human activities caused by land use conversions can also change ecological and hydrological preconditions for the generation of ecosystem services. Such side effects are linked to interventions with the water partitioning process, and are propagated downstream or downwind by the water cycle. They may involve river depletion, altered relations between storm flow and low flow, and consequences for water-dependent downstream activities such as direct water uses, or ecosystem services generated by riparian wetlands and aquatic ecosystems. For example, land-clearing in southwestern Australia caused a rising water table and a threat of saline groundwater seepage into ephemeral watercourses that fed drinking water reservoirs. In the Murray Darling basin and the Hungarian Great Plain, deforestation caused widespread water-logging. Land conversion may also have atmospherically transferred consequences on downwind rainfall (Savenije 1995).

Our scenario of freshwater needs for food production for the additional world population indicates that substantial amounts of freshwater will have to be redirected to croplands from other terrestrial biomes. Increased irrigation and land conversions will produce costly side effects on the capacity of both aquatic (Postel and Carpenter 1997) and terrestrial ecosystems to generate ecosystem services. With a sectoral management and a business-as-usual approach, regional conflicts will probably grow rapidly. Instead of passively allowing unintentional impacts to develop, as in the past, an ability to manage the overall catchment, or the *ecohydrological landscape,* in an intentional manner must be developed.

A few cases of intentional ecohydrological landscape management have been reported from Australia and South Africa, recognizing the interdependence among liquid/vapor freshwater flows, ecosystems services, and human well-being. In Australia, an agreement has been signed between a forest firm and Melbourne City on increasing the rotation time in an upland forest to improve the water source for the city (Jayasuria 1994). In South Africa a permit system has been in operation for several decades, by which the "costs" of afforestation, in terms of river depletion, are estimated (van der Zel 1997). Moreover, the South African fynbos restoration project involves systematic reduction of the invasion of highly water-consuming alien vegetation. The fynbos catchment is seen as an integrated whole, and governance rests on combined ecological and hydrological knowledge and understanding (van Wilgen et al. 1996).

CONCLUSIONS

We have estimated the total water vapor flow from continental ecosystems to be 70,000 km^3/yr, based on generalized field data. Our result captures 97% of the evapotranspiration branch (72,075 km^3/yr) of global freshwater budgets (L'vovich and White 1990). A large part of our water vapor flow (63,200 km^3/yr, or 90%) is attributed to forests, woodlands, wetlands, grasslands, and croplands. These terrestrial biomes sustain society with essential welfare-supporting ecosystem services, including food production.

We do not know the actual freshwater requirements for generating key terrestrial ecosystem services appropriated by the present global human population. To what extent freshwater can be used more efficiently in existing ecosystems is also an open question. Future understanding of complex behavior and interactions within and between ecosystems and freshwater flows may improve this knowledge. We can, however, conclude that earlier global freshwater assessments, which have focused their analysis on the runoff branch of freshwater (e.g., Gleick 1993, UN 1997), have seriously underestimated the human dependence on renewable freshwater flows. Water perceived as unused or even invisible on a human-dominated planet, to a large extent, is already in use for ecosystem support and services to social and economic development.

What are the implications of our results for the management of freshwater, food production, and terrestrial ecosystem services in a world of an expanding human population, intensification in global affairs, and ecological systems undergoing rapid change? Obviously, a shift in perception and approach to water management is necessary. Water is not just an economic commodity to be engineered as input in food production or industrial activities. Water is a fundamental force in ecological life-support systems on which social and economic development depend. Freshwater flows, crop production, and other terrestrial ecosystem services are interconnected and interdependent. Therefore, water appropriation for crop production to a growing human population should no longer be viewed in isolation from potential impacts of freshwater re-directions. It may lead to erosion of critical and welfare-supporting ecosystem services in both terrestrial and aquatic systems, and potential conflicts between upstream and downstream users.

Land use choices are also water choices, and will always lead to alterations in the flow of freshwater and ecosystem services elsewhere. This trade-off is made explicit in our scenario of freshwater for crop production to support a growing human population. It has to become embedded in the management of dynamic freshwater ecosystem linkages, in what we call the ecohydrological landscape. The challenge is immense and will require co-management at catchment levels, often crossing administrative and even national boundaries.

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RESPONSES TO THIS ARTICLE

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Acknowledgments:

This article is the product of an interdisciplinary team work, where the contributions of the authors successively grew out from their starting contributions (Falkenmark's and Folke's conceptual bridge building, Rockström's methodology development and Gordon's and Engvall's in depth data analysis). Gordon's work is supported by the Swedish Council for Forestry and Agricultural Research (SJFR), and Folke's partly by the Pew Scholars program of The Pew Charitable Trusts.

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