

Copyright ©1999 by The Resilience Alliance*

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/>

A version of this article in which text, figures, tables, and appendices are separate files may be found by following this [link](#).

Research

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

[Johan Rockström](#)^{1,2}, [Line Gordon](#)², [Carl Folke](#)^{2,3}, [Malin Falkenmark](#)^{4,5}, and [Maria Engwall](#)²

¹*RELMA*; ²*Stockholm University*; ³*Beijer International Institute of Ecological Economics*; ⁴*Swedish Natural Science Research Council*; ⁵*Stockholm International Water Institute (SIWI)*

- [Abstract](#)
- [Introduction](#)
- [Invisible Green Water Vapor and Visible Blue Liquid Water](#)
- [Estimating Water Vapor Flows of Major Terrestrial Biomes](#)
 - [Grasslands, Wetlands, Woodlands, and Forests](#)
 - [Croplands](#)
 - [Results of Water Vapor Estimates of Major Terrestrial Biomes](#)
- [Estimating Total Water Vapor Flows from Continents](#)
- [Interrelations between Water Vapor Flows and Terrestrial Ecosystem Services](#)
- [Freshwater, Food, and Ecosystem Services for a Growing Human Population](#)
- [Intentional Ecohydrological Landscape Management](#)
- [Conclusions](#)
- [Responses to this Article](#)
- [Acknowledgments](#)
- [Literature Cited](#)
- [Appendix 1: Total water vapor flows from croplands](#)
- [Appendix 2: Total water vapor flow from forests/woodlands, wetlands, and grasslands](#)
- [Appendix 3: Estimating evaporating surface runoff from croplands](#)
- [Appendix 4: Cited literature in appendices](#)

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 km³/yr (ranging from 56,000 to 84,000 km³/yr). Of this flow, 90% is attributed to forests, including woodlands (40,000 km³/yr), wetlands (1400 km³/yr), grasslands (15,100 km³/yr), and croplands (6800 km³/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.

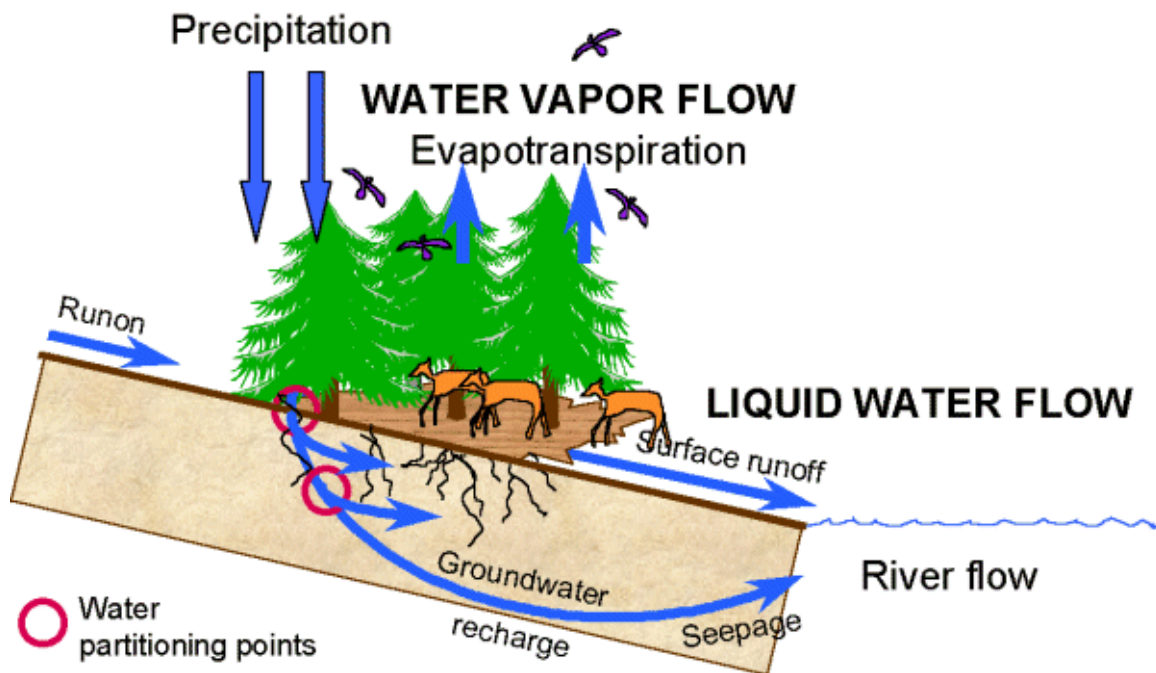
We begin to address the complex, but largely neglected, issue of the interplay among water vapor flows, agricultural food production, and the generation of ecosystem services in terrestrial biomes. Our findings highlight the fact that the critical issue of how to feed a growing human population through 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.

Fig. 1. The hydrological cycle, showing the repartitioning of rainfall into vapor and liquid freshwater flow (modified from Jansson et al. 1999).



Previous estimates, e.g., L'vovich and White (1990), have calculated ET indirectly as the difference between precipitation, P , over continents ($110,305 \text{ km}^3/\text{yr}$) and total runoff, R , ($38,230 \text{ km}^3/\text{yr}$), arriving at $72,075 \text{ km}^3/\text{yr}$. 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 per year) 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).

Table 1. Total water vapor estimates with the classification of biomes and vegetation subgroups.

Biome	Vegetation subgroups	Climatic zone	Land surface ^a	n ^k	Actual evapotranspiration (mm/yr)			Water vapor estimates (km ³ /yr)		
					Mean	Low	High	Mean	Low	High
			1000 km ²							
Forest, woodlands	taiga	boreal	11,560	3	401	380	420	4636	4393	4855
	predominantly coniferous	temperate	3500	4	487	395	580	1705	1383	2030
	predominantly deciduous	temperate	8500	4	729	588	964	6199	4998	8194
	woodland/woody savannah	temperate	5200	3	416	300	530	2165	1560	2756
	forest, dry/deciduous/seasonal	tropical/subtropical	7400	2	792	783	800	5857	5794	5920
	forest, wet	tropical/subtropical	5300	3	1245	880	1493	6600	4664	7913
	savannah/woodland, dry	tropical/subtropical	12,700	2	882	870	894	11,201	11,049	11,354
	savannah/woodland, wet	tropical/subtropical	1300	3	1267	1100	1500	1647	1430	1950
Subtotal								40,009	35,271	44,972
Wetland	bog	boreal	651	3	221	200	260	144	130	169
	bog	temperate	488	4	674	456	1020	329	223	498
	swamp	temperate	41	3	843	670	720	35	27	30
	swamp	subtropical	16	5	1127	930	1277	18	15	20
	swamp ^b	tropical	508	1	1656	1408	1904	841	715	967
Subtotal								1366	1110	1684
Grasslands	cool grassland	mostly temperate	6940	16	410	130	633	2843	900	4393
	mountainous grassland	temperate	650	4	655	430	951	426	280	618
	warm and hot grassland	mostly tropical	17,300	7	599	403	862	10,356	6967	14,913
	mountainous grassland ^c	tropical	650	1	600	402	798	390	261	519
	dry shrubland	tropical	4000	2	270	225	315	1080	900	1260
Subtotal								15,095	9308	21,702
			Production (10³ Mg/yr)^d	n	Water Use Efficiency (m³/Mg)^e					
Croplands	cereals, grain	temperate	790,476	15	1309	539	2643	1095	564	1919

	cereals, grain	tropical	625,409	10	1438	591	4369	764	555	1178
	cereals, total DM ^f	temperate	4011	19	438	240	646	56	31	83
	cereals, total DM ^f	tropical	664,404	3	331	271	372	235	217	247
	cotton lint		18,509	3	5454	4227	6313	101	78	117
	cotton seed		86,925	1	2083	1667	2500	181	144	217
	fibers		5541	4	574	278	870	3	2	5
	forage		725,032	19	934	172	2810	641	249	1403
	fruit	temperate	208,348	2	269	163	375	58	34	78
	fruit	tropical	232,748	3	259	150	350	60	35	81
	natural rubber/gums		6088	2	30,137	29,167	31,108	183	178	189
	nuts ^g		6929	1	415	200	1080	2	1	6
	oil-bearing crops	temperate	35,454	3	1892	1530	2117	64	54	72
	oil-bearing crops	tropical	55,225	2	3083	2667	3500	71	70	92
	oil palm ^h		6,604,000 km ²	1	1500 mm	1250 mm	1750 mm	242	212	278
	pulses, dry seed	temperate	43,493	3	3355	1731	5833	157	75	197
	pulses, dry seed	tropical	166,338	5	1866	1250	3003	283	214	370
	pulses, green seed	temperate	9326	2	1149	583	1714	12	5	16
	rice		540,838	4	1099	839	1404	594	454	759
	roots and tubers	temperate	558,137	7	286	139	402	144	94	217
	roots and tubers ^g	tropical	330,786	1	616	369	1299	204	122	430
	roots, tubers for fodder ^f	temperate	11,105	8	326	157	616	4	2	7
	spices ⁱ		4091	0	1000	800	1500	4	3	6
	stimulant crops		791	3	4515	2083	6983	33	28	74
	sugar cane		1,120,898	3	123	100	163	138	112	182
	vegetables ^j		549,683	6	147	35	500	75	22	242
Subtotal								5404	3552	8427
Total								61,879	49,280	76,800

- a Land surfaces for forests and grasslands are derived from Olson et al. (1983); land surfaces for wetlands are from Matthews (1983).
- b Low/high values are based on the mean +/- 15%.
- c Low/high values are based on the mean +/- 33%, based on the average standard deviation of the other subgroups in grasslands.
- d Production data are from the FAO (Faostat 1997).
- e Note that only the aggregate average WUE values for similar crops are presented in Table 1. For example, the WUE values and the water vapor estimates for cereals/temperate in Table 1 are derived from individual values for each major cereal (wheat, barley, oats, rye, and buckwheat).
- f The WUE was calculated based on the total dry matter yield.
- g The mean WUE comes from only one article; the low and high are the variations within that article.
- h For oil palms, which are harvested on the same area for oil, kernels, and fruit, the total freshwater used was calculated by

$$\text{area harvested} = \text{oil produced (Mg)} / \text{production of oil (Mg/ha)}$$

$$\text{total water vapor used} = \text{area harvested (km}^2\text{)} \times \text{ET from palm stands (m)}$$

Palm oil production (6,603,778 Mg) was collected from the FAO (Faostat 1997). The production was assumed to be 1.75 Mg/ha (Mémento de l'Agronome 1984). The ET from palm stands is 1500 mm (Jackson 1989). The variation of ET was assumed to be 125 mm. The minimum and maximum calculation for oil palm was therefore based on the ET rates of 1375 mm and 1725 mm. The same values were used for low/high calculations.

- i Spices is a small group, covering only about 0.045% of the total global area harvested each year (Faostat 1997). There is also a large variation in species composition, as well as in parts of the plant used for production measurement. The WUE was, therefore, based on a qualified assumption. The WUE was assumed to be 1000 m³/Mg. The minimum was assumed to be 800 m³/Mg, the maximum as 1500 m³/Mg, and the standard deviation as 200 m³/Mg. Spices are often just a small part of a plant, why the WUE will be higher if the whole plant is considered.
- j For vegetables that were produced as feed, the WUE was calculated based on the grain yield of that specific crop or group of crops.
- k The number of references.

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 Djiteye 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 km³/yr (Table 2). We estimated the total water vapor flow from grasslands to be 15,100 km³/yr (range 9300 to 21,700 km³/yr); from forests and woodlands to be 40,000 km³/yr (range 35,300 - 45,000 km³/yr); and from wetlands to be 1400 km³/yr (range of 1100 - 1700 km³/yr) (Table 1). The total water vapor flow in the world's croplands for crop production was estimated as 5400 km³/yr, with low/high values ranging from 3600 to 8400 km³/yr. Adding ET for non-economic plant growth on agricultural lands of 1300 km³/yr gives a mean water vapor flow of 6700 km³/yr, ranging from 4900 to 9800 km³/yr.

Table 2. Bottom-up estimate of global water vapor flows from the continents.

Water vapor source		Our estimates (km ³ /yr)	Earlier estimates (km ³ /yr)	References
Major terrestrial biomes				
Croplands		6800	2285 - 5500	Postel et al. (1996), Shiklomanov (1996), Postel (1998)
Temperate and tropical grasslands		15,100	5800	Postel et al. (1996)
Temperate and tropical forests, woodlands, and taiga		40,000	6800	Postel et al. (1996)
Bogs, fens, swamps, and marshes		1400		
	Subtotal	63,200	14,885 - 18,100	
Other systems				
Green areas in urban settlements		100	100	Postel et al. (1996)
Upstream rural water use		210		
Lake evaporation		600	600	L'vovich (1979)
Evaporation from large reservoirs (>100 x 10 ⁶ m ³)		130	130	L'vovich and White (1990)
Evaporation from small reservoirs (<100 x 10 ⁶ m ³)		30		
Tundra and deserts		5700		
	Subtotal	6800	830	
	Total	70,000	15,715 - 18,930	

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 m³ 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 m³/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 km³/yr for crops.

The aggregate estimate in Table 1 ranges from 49,000 to 77,000 km³/yr, which is roughly a deviation of 14,000

km³/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 km³/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 km³/yr, and of harvested forest products to be 6800 km³/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 km³/yr.

In summary, earlier estimates suggest that humans depend on some 14,900-15,800 km³/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 km³/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 km³/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 km³/yr (Postel et al. 1996), and vapor flows from lakes account for an estimated 600 km³/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 km³/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 m³ 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 km³ when full). Based on this, we have estimated the vapor flow from small reservoirs as 30 km³/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 10⁶ m³) return an estimated 130 km³/yr of vapor flow to the atmosphere (L'vovich and White 1990).

Tundra and deserts, covering some 31 x 10⁶ km² of land (Olson et al. 1983), with an average annual ET of 180 mm (Frank and Inouye 1994), return approximately 5730 km³ 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 km³/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 km³/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 CO₂, 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 driver in 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 $1180 \text{ m}^3/\text{yr}$, 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 $2650 \text{ m}^3 \text{ p}^{-1} \text{ yr}^{-1}$ 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 $86 \text{ km}^3/\text{yr}$ to $2570 \text{ km}^3/\text{yr}$ 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 $3100 \text{ km}^3/\text{yr}$ in 2025. This would imply a total crop water demand in 2025 of about $9,800 \text{ km}^3/\text{yr}$, 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 $425 \text{ km}^3/\text{yr}$, 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 $300 \text{ km}^3/\text{yr}$. 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 also would 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 $300 \text{ km}^3/\text{yr}$. 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 $1000 \text{ km}^3/\text{yr}$ out of $3100 \text{ km}^3/\text{yr}$, 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 $2100 \text{ km}^3/\text{yr}$ of additional water vapor needed by the total water vapor from our estimates in tropical grasslands, forests, woodlands, and wetlands, which amounts to $38,000 \text{ km}^3/\text{yr}$, 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 CO₂ 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 km³/yr, based on generalized field data. Our result captures 97% of the evapotranspiration branch (72,075 km³/yr) of global freshwater budgets (L'vovich and White 1990). A large part of our water vapor flow (63,200 km³/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.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a comment, follow [this link](#). To read comments already accepted, follow [this link](#).

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.

LITERATURE CITED

Ajtay, G. L., P. Ketner, and P. Duvigneaud. 1979. Pages 129-182 in B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, editors. *The global carbon cycle*. John Wiley, New York, New York, USA.

Baskin, Y. 1997. *The work of nature: how the diversity of life sustains us*. Island Press, Washington, D.C., USA.

Bisonette, J. A., editor. 1997. *Wildlife and landscape ecology: effects on pattern and scale*. Springer Verlag, New York, New York, USA.

Costanza, R., R. d'Arge, R. deGroot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* **387**:253-260.

Daily, G. C., editor. 1997. *Nature's services - human dependence on natural ecosystems*. Island Press, Washington, D.C., USA.

Dancette, C. 1983. Besoins en eau du mil au Sénégal - Adaptations en zone semi-aride tropicale. *L'Agronomie Tropicale* **38**:267-280.

de Groot, R. S. 1992. *Functions of nature: evaluation of nature in environmental planning, management, and decision making*. Wolters-Noordhoff, Groningen, the Netherlands.

Falkenmark, M. 1995. Pages 15-16 in FAO Land and Water Bulletin Number 1. Land and Water Integration and River Basin Management, FAO, Rome, Italy.

_____. 1997. Meeting water requirements of an expanding world population. *Philosophical Transactions of the Royal Society of London B* **352**:929-936.

Falkenmark, M., W. Klohn, J. Lundqvist, S. Postel, J. Rockström, D. Seckler, S. Hillel, and J. Wallace. 1998. Water scarcity as a key factor behind global food insecurity: Round table discussion. *Ambio* **21**(2): 148 - 154.

FAO. 1995. World Agriculture: towards 2010. N. Alexandratos, editor. John Wiley, Chichester, UK.

Faostat. 1997. Electronic database available on the internet <http://apps.fao.org>. FAO, Statistics Division, Rome, Italy. [Data were taken 09/26/97.]

Folke, C. Socio-economic dependence on the life-support environment. 1991. Pages 77-94 in C. Folke and T. Kåberger, editors. *Linking the natural environment and the economy: essays from the Eco-Eco Group*. Kluwer Academic, Dordrecht, the Netherlands.

Frank, D. A., and R. S. Inouye. 1994. Temporal variation in actual evapotranspiration of terrestrial ecosystems: patterns and ecological implications. *Journal of Biogeography* **21**:401-411.

Gleick, P. H., editor. 1993. *Water in crisis*. Oxford University Press, New York, New York, USA.

_____. 1996. Basic water requirements for human activities: meeting basic needs. *Water International* **21**:83-92.

Holling, C. S. 1986. The resilience of terrestrial ecosystems: local surprise and global change. Pages 292-317 in W. C. Clark and R. E. Munn, editors. *Sustainable development of the biosphere*. Press Syndicate of the University of Cambridge, Cambridge, UK.

_____. 1994. An ecologist's view of the Malthusian conflict. Pages 79-103 in K. Lindahl-Kiessling and H. Landberg, editors. *Population, economic development, and the environment*. Oxford University Press, Oxford, UK.

Jackson, I. J. 1989. *Climate, water and agriculture in the tropics*. Longman Scientific and Technical, New York, New York, USA.

Jansson, A.-M., M. Hammer, C. Folke, and R. Costanza, editors. 1994. *Investing in natural capital*. Island Press, Washington, D.C., USA.

Jansson, Å., C. Folke, J. Rockström, and L. Gordon. 1999. Linking freshwater flows and ecosystem services appropriated by people: the case of the Baltic Sea drainage basin. *Ecosystems*, in press.

Jayasuriya, D. 1994. Value proposition as a tool for conflict resolution in natural resources utilization. Paper presented at a seminar on Integration of Land and Water Management, 24-25 October 1994. Natural Resources Management Institute, Stockholm University, Stockholm, Sweden.

L'vovich, M. I. 1979. *World water resources and their future*. LithoCrafters, Chelsea, UK.

L'vovich, M. I., and G. F. White. 1990. Use and transformation of terrestrial water systems. Pages 235-252 in B. L. Turner II, W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews, and W. B. Meyer, editors. *The Earth as transformed by human action*. Cambridge University Press, Cambridge, UK.

Le Houerou, H. N. 1984. Rain use efficiency: a unifying concept in arid-land ecology. *Journal of Arid Environments* **7**:213-247.

Liang, Y. M., D. L. Hazlett, and W. K. Laurenroth. 1989. Biomass dynamics and water use efficiencies of five plant communities in the shortgrass steppe. *Oecologia* **80**:148-153.

Lubchenco, J. 1998. Entering the century of the environment: a new social contract for science. *Science*

279: 491-496.

Lundqvist, J. 1998. Avert looming hydrocide. *Ambio* **27**: 428-433.

Lundqvist, J., and P. Gleick. 1997. Sustaining our waters into the 21st century. *Background Report No.4 of the Comprehensive assessment of the freshwater resources of the world.* WMO-SEI, Stockholm, Sweden.

Matson, P. A., W. J. Parton, A. G. Power, and M. J. Swift. 1997. Agricultural intensification and ecosystem properties. *Science* **277**: 504-509.

Matthews, E. 1983. Global vegetation and land use: new high-resolution databases for climate studies. *Journal of Climate and Applied Meteorology* **22**: 474-487.

Mémento de l'Agronome. 1984. Ministère de la coopération et du développement, Paris, France.

Mitch, W. J., and J. G. Gosselink. 1983. *Wetlands.* Van Nostrand Reinhold, New York, New York, USA.

Nulsen, R. A., K. J. Bligh, I. N. Baxter, E. J. Solin, and D. H. Imrie. 1986. The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. *Australian Journal of Ecology* **11**: 361-371.

Odum, E. P. 1989. *Ecology and our endangered life-support systems.* Sinauer Associates, Sunderland, Massachusetts, USA.

Olson, J. S., J. A. Watts, and L. J. Allison. 1983. *Carbon in live vegetation of major world ecosystems.* Oak Ridge National Laboratory, Environmental Science Division, Report ORNL-5862, Oak Ridge, Tennessee, USA.

Penman, H. L. 1963. Natural evaporation from open water, bare soil, and grass. *Proceedings of the Royal Society, London, Series A* **193**: 120-145.

Penning de Vries, F. W. T., and M. A. Djitéye, editors. 1982. *La productivité des pâturages Sahéliens : une étude des sols, des végétations et de l'exploitation de cette ressource naturelle.* Pudoc, Wageningen, the Netherlands.

Peterson, G., C. R. Allen, and C. S. Holling. 1998. Ecological resilience, biodiversity, and scale. *Ecosystems* **1**: 6-18.

Postel, S. L. 1998. Water for food production: will there be enough in 2025? *BioScience* **48**: 629-637.

Postel, S., and S. Carpenter. 1997. Freshwater ecosystem services. Pages 195-214 in G. C. Daily, editor. *Nature's services - human dependence on natural ecosystems.* Island Press, Washington, D.C., USA.

Postel, S. L., G. C. Daily, and P. R. Ehlich. 1996. Human appropriation of renewable fresh water. *Science* **271**: 785-788.

Rockström, J. 1997. On-farm agrohydrological analysis of the Sahelian yield crisis: Rainfall partitioning, soil nutrients and water use efficiency of pearl millet. Dissertation. Stockholm University. Akademityck AB, Edsbruk, Sweden.

Rockström, J., P-E. Jansson, and J. Barron. 1998. Seasonal rainfall partitioning under runoff and runoff conditions on sandy soil in Niger - on-farm measurements and water balance modelling. *Journal of Hydrology* **210**: 68-92.

Rockström, J., and C. Valentin. 1997. Hillslope dynamics of on-farm generation of surface water flows: The case of rainfed cultivation of pearl millet in the Sahel. *Agricultural Water Management* **33**: 183-210.

Savenije, H. H. G. 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. *Journal of Hydrology* **167**: 57-78.

Shiklomanov, I. A. 1996. *Assessment of water resources and water availability in the world.* State Hydrological Institute, St. Petersburg, Russia.

_____. 1997. Assessment of water resources and water availability of the world. *Background Report No.2 of the Comprehensive assessment of the freshwater resources of the world.* WMO-SEI, Stockholm, Sweden.

Sinclair, T. R., C. B. Tanner, and J. M. Bennett. 1984. Water-use-efficiency in crop production. *BioScience* **34**: 36-40.

Swank, W. T., L. W. Swift Jr., and J. E. Douglas. 1988. Stream flow changes associated with forest cutting, species composition, and natural disturbances. Pages 297-312 in W. T. Swank and D. A. Crossley Jr., editors. *Forest hydrology and ecology at Coweeta*. Springer-Verlag, New York, New York, USA.

Thornwaite, C. W., and J. R. Mather. 1955. The water balance. *Climatology* **8**: 1-87.

UN-SEI. 1997. *Comprehensive assessment of the freshwater resources of the world*. WMO-SEI, Stockholm, Sweden.

van der Zel, D. W. 1997. Sustainable industrial afforestation in South Africa under water and other environmental pressures. Pages 217-225 in D. Rosbjerg, editor. *Sustainability of water resources under increasing uncertainty*. Proceedings of the Rabat Symposium. IAHS Press, Wallingford, UK.

van Wilgen, B. W., R. M. Cowling, and C. J. Burgers. 1996. Valuation of ecosystem services: a case study from a South African fynbos ecosystem. *BioScience* **46**: 184-189.

Vitousek, P. M., P. R. Ehrlich, A. H. Ehrlich, and P. A. Matson. 1986. Human appropriation of the products of photosynthesis. *BioScience* **36**: 368-373.

Walker, B. H. 1993. Rangeland ecology: understanding and managing change. *Ambio* **22**: 80-87.

WRI. 1994. *World Resources 1994-1995*. Oxford University Press, Oxford, UK.

APPENDIX 1

Total water vapor flows from croplands, with data and references for calculation and classification of subgroups.

Subgroup	Climatic zone	Crop	Yield ^a (10 ³ Mg/yr)	n	WUE (m ³ /Mg)			Water vapor flow (km ³ /yr)			References
					Mean	Low	High	Mean	Low	High	
Cereals grain	temperate			15	1309	539	2643				
		barley	159,021	6	1070	539	1575	170, 7	85, 71	250, 39	1, 16, 29, 30, 23, 35
		oats	32,710	1	1368			44, 75	17, 63	86, 45	35
		wheat	557,420	8	1482	787	2643	826, 19	438, 70	1473, 14	6, 13, 14, 16, 23, 35, 44
		rye	25,054					32, 81	13, 50	66, 21	
		buckwheat	2892					3, 79	1, 56	7, 64	
		triticale	6341					8, 30	3, 42	16, 76	
		cereals nes*	2098					2, 75	1, 13	5, 54	
		mixed grain	4940					6, 47	2, 66	13, 6	
Cereals grain	tropical			10	1438	591	4369				
		maize	533,732	4	1151	938	1456	614, 56	500, 37	777, 7	13, 22, 34, 41
		millet/ sorghum	91,188	6	1629	591	4369	148, 56	53, 85	398, 39	13, 16, 34, 41, 44
		quinoa	33					0, 5	0, 2	0, 14	

		fonio	203					0, 29	0, 12	0, 89	
		canary seed	253					0, 36	0, 15	1, 11	
Cereals, total DM ^b	temperate			19	438	240	646				1, 2, 6, 12, 14, 20, 23, 26, 29, 30, 45
		rye grass for forage	4011					1, 76	0, 96	2, 59	
		straw husks	124,221					54, 44	29, 85	80, 20	
Cereals, total DM ^b	tropical			3	331	271	372				
		maize for forage	470,124	2	361	349	372	169, 48	164, 7	174, 89	12, 45
		sorghum for forage	50,545	1	271			13, 70	13, 70	18, 80	45
		green corn (maize)	7270					2, 40	1, 97	2, 70	
		forage products nes	136,465					49, 20	36, 98	50, 77	
Nuts ^c				1	415	200	1080				
		karite nuts (sheanuts)	620					0, 26	0, 12	0, 67	
		brazil nuts	57					0, 0	0, 0	0, 0	
		kolanuts	303					0, 26	0, 12	0, 67	
		cashew nuts	670					0, 2	0, 1	0, 6	
		chestnuts	497					0, 13	0, 6	0, 33	
		tung nuts	631					0, 28	0, 13	0, 72	
		almonds	1212					0, 21	0, 10	0, 54	
		walnuts	1002					0, 26	0, 13	0, 68	
		pistachios	386	1	415	200	1080	0, 16	0, 8	0, 42	25
		hazelnuts (filberts)	629					0, 42	0, 20	1, 8	
		areca nuts (betel)	487					0, 16	0, 8	0, 42	
		nuts nes	434					0, 26	0, 13	0, 68	
Pulses dry seed	temperate			3	3355	1731	5833				
		beans, dry	17,142	2	2116	1731	2500	36, 27	29, 68	42, 85	5, 13
		broad beans, dry	3227					10, 83	5, 59	18, 82	
		peas, dry	12,960	1	5833			75, 60	22, 44	75, 60	13
		lentils	2773					9, 30	4, 80	16, 18	
		vetches	1010					3, 39	1, 75	5, 89	
		lupines	1407					4, 72	2, 44	8, 20	
		string beans	1352					4, 54	2, 34	7, 89	
		pulses, nes	3623					12, 15	6, 27	21, 13	

Pulses dry seed	tropical			5	1866	1250	3003				
		soybeans	124,318	2	1607	1250	1964	199, 80	155, 40	244, 20	3, 13
		pigeon peas	3192					5, 96	3, 99	9, 59	
		bambara beans	54					0, 10	0, 7	0, 16	
		chickpeas	7673					14, 32	9, 59	23, 04	
		cow peas, dry	2331					4, 35	2, 91	7, 0	
		groundnuts in shell	27,514	3	2039	1458	3003	56, 9	40, 13	82, 63	9, 13, 34
		castor beans	1257					2, 35	1, 57	3, 77	
Pulses green seed	temperate			2	1149	583	1714				
		beans, green	3470	1	583			2, 2	2, 2	5, 95	13
		peas, green	4901	1	1714			8, 40	2, 86	8, 40	13
		broad beans, green	955					1, 10	0, 56	1, 64	
Roots and tubers	temperate			7	286	139	402				
		potatoes	285,968	4	246	196	402	70, 41	56, 17	114, 96	13, 42
		roots and tubers nes	4166					1, 19	0, 58	1, 67	
		sugar beets	267,498	3	268	139	373	71, 77	37, 15	99, 78	10, 13
		sugar crops nes	504					0, 14	0, 7	0, 20	
Roots and tubers ^c	tropical			1	616	369	1299				
		sweet potatoes	130,426					80, 32	48, 13	169, 38	
		cassava	163,097	1	616	369	1299	100, 44	60, 18	211, 81	48
		yautia (cocoyam)	185					0, 11	0, 7	0, 24	
		taro (coco yam)	5520					3, 40	2, 4	7, 17	
		yams	31,557					19, 43	11, 64	40, 98	
Roots and tubers for fodder ^b	temperate			8	326	157	616				10, 12, 42, 46, 48
		beets for fodder	10,991					3, 58	1, 73	6, 77	
		swedes for fodder	114					0, 4	0, 2	0, 7	
Fruit	temperate			2	269	163	375				
		apples	49,422					13, 28	8, 3	18, 53	
		pears	11,737					3, 15	1, 91	4, 40	

sour cherries	1348					0, 36	0, 22	0, 51	
cherries	1751					0, 47	0, 28	0, 66	
watermelons	38,820	1	163			6, 31	6, 31	14, 56	13
peaches and nectarines	10,531					2, 83	1, 71	3, 95	
plums	6684					1, 80	1, 9	2, 51	
stonefruit nes fresh	330					0, 9	0, 5	0, 12	
strawberries	2539					0, 68	0, 41	0, 95	
raspberries	319					0, 9	0, 5	0, 12	
gooseberries	192					0, 5	0, 3	0, 7	
currants	691					0, 19	0, 11	0, 26	
blueberries	152					0, 4	0, 2	0, 6	
cranberries	228					0, 6	0, 4	0, 9	
berries nes	297					0, 8	0, 5	0, 11	
grapes	56,737	1	375			21, 28	9, 22	21, 28	13
figs	1101					0, 30	0, 18	0, 41	
fruit fresh nes	25,468					6, 84	4, 14	9, 55	
		3	259	150	350				
persimmons	1373					0, 35	0, 21	0, 48	
cashew apple	1306					0, 34	0, 20	0, 46	
bananas	53,734	1	276			14, 81	8, 6	18, 81	13
plantains	28,145					7, 28	4, 22	9, 85	
oranges	56,021					14, 48	8, 40	19, 61	
mandarins, clementines, etc.	14,763					3, 82	2, 21	5, 17	
lemons and limes	8803					2, 28	1, 32	3, 8	
grapefruit and pomelo	4781					1, 24	0, 72	1, 67	
citrus fruit nes	3995	1	350			1, 40	0, 60	1, 40	13
quinces	323					0, 8	0, 5	0, 11	
apricots	2360					0, 61	0, 35	0, 83	
mangos	18,408					4, 76	2, 76	6, 44	
avocados	208					0, 5	0, 3	0, 7	
pineapples	11,441	1	150			1, 72	1, 72	4, 0	13
dates	4278					1, 11	0, 64	1, 50	
kiwi fruit	917					0, 24	0, 14	0, 32	

Fruit

tropical

		papaya	5612					1, 45	0, 84	1, 96	
		kapok fruit	437					0, 11	0, 7	0, 15	
		fruit, tropical nes	7417					1, 92	1, 11	2, 60	
		coffee, green	5770					1, 49	0, 87	2, 2	
		cocoa beans	2655					0, 69	0, 40	0, 93	
Oil-bearing crops	temperate			3	1892	1530	2117				
non-wooded		rapeseed	29,595	2	1780	1530	2029	52, 67	45, 28	60, 5	7, 35
		mustard seed	469	1	2117			0, 99	0, 72	0,99	47
		hempeed	36					0, 7	0, 5	0, 8	
		linseed	2351					4, 45	3, 60	4, 98	
		poppy seed	41					0, 8	0, 6	0, 9	
		oilseeds nes	1458					2, 76	2, 23	3, 9	
		vegetable tallow	117					0, 22	0, 18	0, 25	
		tallowtree seeds	781					1, 48	1, 19	1, 65	
		melon seed	607					1, 15	0, 93	1, 28	
Oil-bearing crops	tropical			2	3083	2667	3500				
non-wooded		safflower seed	753	1	2667			2, 1	2, 1	2, 63	13
		sunflower	23,004	1	2667			61, 34	61, 34	80, 51	13
		sesame seed	2432					7, 50	6, 49	8, 51	
		stillinga oil	117					0, 36	0, 31	0, 41	
woody	tropical										
		coconuts ^d	$10.3 \times 10^6 \text{ km}^2$		1320 mm	1200 mm	1500 mm	136, 17	123, 79	154, 74	
		palm oil, palm kernels, oil palm fruit ^d	$6.6 \times 10^6 \text{ km}^2$		1500 mm	1250 mm	1750 mm	99, 6	82, 55	115, 57	
		olives	11,100	1	583	500	667	6, 47	5, 55	7, 40	13
Fibers				4	574	278	870				2, 6, 12
		flax fiber and tow	571					0, 33	0, 16	0, 50	
		kapokseed in shell	328					0, 19	0, 9	0, 29	
		hemp fiber and tow	102					0, 6	0, 3	0, 9	
		jute	2619					1, 50	0, 73	2, 28	

	jute-like fibers	618					0, 35	0, 17	0, 54	
	ramie	106					0, 6	0, 3	0, 9	
	sisal	333					0, 19	0, 9	0, 29	
	agave fibers nes	55					0, 3	0, 2	0, 5	
	coir	172					0, 10	0, 5	0, 15	
	abaca (manila hemp)	106					0, 6	0, 3	0, 9	
	fiber crops nes	423					0, 24	0, 12	0, 37	
	kapok fiber	107					0, 6	0, 3	0, 9	
Vegetables ^e			6	147	35	500				
	onions + shallots, green	3287	1	113			0, 37	0, 12	1, 64	13
	onions, dry	33765					4, 95	1, 19	16, 88	
	leeks + other alliac. veg.	1493					0, 22	0, 5	0, 75	
	garlic	9211					1, 35	0, 32	4, 61	
	carrots	15,226					2, 23	0, 54	7, 61	
	chicory roots	399					0, 6	0, 1	0, 20	
	tomatoes	80,192	2	83	74	92	6, 63	5, 90	7, 35	13, 33
	pumpkins squash gourds	9060					1, 33	0, 32	4, 53	
	cucumbers and gherkins	21,192					3, 11	0, 75	10, 60	
	eggplants	10,591					1, 55	0, 37	5, 30	
	chillies + peppers, green	12,955	1	500			6, 48	0, 46	6, 48	13
	okra	1274					0, 19	0, 4	0, 64	
	cantaloupes + melons	15,216					2, 23	0, 53	7, 61	
	cabbages	44,618	1	67			2, 97	1, 57	22, 31	13
	artichokes	1163					0, 17	0, 4	0, 58	
	asparagus	2763					0, 41	0, 10	1, 38	
	lettuce	12,722	1	35			0, 45	0, 45	6, 36	36
	spinach	5648					0, 83	0, 20	2, 82	
	cauliflower	11812					1, 73	0, 42	5, 91	
vegetables, fresh nes	186,836					27, 39	6, 57	93, 42		

	cabbage for fodder	2184					0, 32	0, 8	1, 9	
	pumpkins for fodder	743					0, 11	0, 3	0, 37	
	turnips for fodder	2336					0, 34	0, 8	1, 17	
	leaves and tops vines	19461					2, 85	0, 68	9, 73	
	vegetables, canned nes	807					0, 12	0, 3	0, 40	
	carobs	249					0, 4	0, 1	0, 12	
	carrots for fodder	90					0, 1	0, 0	0, 4	
	vegetables + roots for fodder	44,393					6, 51	1, 56	22, 20	
Spices ^f		0	0	1000	800	1500				
	peppermint	55					0, 5	0, 4	0, 8	
	pyrethrum, dried	18					0, 2	0, 1	0, 3	
	pepper	229					0, 23	0, 18	0, 34	
	pimento allspice	1896					1, 90	1, 52	2, 84	
	vanilla	5					0, 0	0, 0	0, 1	
	cinnamon (canela)	66					0, 7	0, 5	0, 10	
	cloves, whole + stems	133					0, 13	0, 11	0, 20	
	nutmeg, mace, cardamom	59					0, 6	0, 5	0, 9	
	anise, badian, fennel	182					0, 18	0, 15	0, 27	
	ginger	591					0, 59	0, 47	0, 89	
	spices nes	856					0, 86	0, 68	1, 28	
Forage			19	934	172	2810				
	hay, non-leguminous	87,514					81, 72	15, 1	245, 89	
	hay (unspecified)	59,689					55, 74	10, 24	167, 71	
	grasses nes for forage	23,2015	6	758	429	1031	175, 95	99, 58	239, 26	24, 37, 43
	clover for forage	64,155	8	1117	172	2810	71, 67	11, 0	180, 26	2, 24, 31, 32
	alfalfa for forage	160,767	5	890	573	1432	143, 1	92, 12	230, 17	8, 13, 20, 32, 45,

	leguminous f. forage	49,601					46, 32	8, 51	139, 37	
	hay (clover lucerne)	4991					4, 66	0, 86	14, 2	
	range pasture	59,800					55, 84	10, 26	168, 2	
	improved pasture	6500					6, 7	1, 11	18, 26	
Stimulant			3	4515	2083	6983				
	tea	2587	2	5730	4478	6983	14, 83	11, 58	18, 7	40, 28
	tobacco leaves	7217	1	2083			15, 3	15, 3	50, 40	13
	mate	668					3, 2	1, 39	4, 67	
	hops	122					0, 55	0, 25	0, 85	
Natural rubber/gum			2	30,137	29,167	31,108				
	natural rubber	6065	2	30,137	29,167	31,108	182, 80	176, 91	188, 68	11, 50
	natural gums	22					0, 68	0, 66	0, 70	
Sugar cane	sugar cane	1,120,898	3	123	100	163	137, 84	111, 53	182, 15	13, 15, 49
Rice	rice paddy	540,838	4	1099	839	1404	594, 34	453, 65	759, 36	13, 34, 38, 44
Cotton seed	cotton seed	86,925	1	2083	1667	2500	181, 9	144, 88	217, 31	13
Cotton lint	cotton lint	18,509	3	5454	4227	6313	100, 96	78, 24	116, 84	17, 19, 27
Subtotal:							5410	3591	8442	

Reference numbers: (1) Andersen et al. 1992; (2) Armstrong et al. 1994; (3) Ashley 1983; (4) Barker et al. 1989; (5) Barros and Hanks 1993; (6) Beech and Leach 1989; (7) Bhan et al. 1980; (8) Bolger and Matches 1990; (9) Boote 1983; (10) Brown et al. 1987; (11) Bucks et al. 1985; (12) Black 1971; (13) Doorenbos and Kassam 1979; (14) Entz and Fowler 1991; (15) Gascho and Shih 1983; (16) Gregory 1988; (17) Grimes et al. 1969; (18) Hattendorf et al. 1988; (19) Hearn 1980; (20) Heichel 1983; (21) Heitholt 1989; (22) Hillel and Guron 1973; (23) Imtiyaz et al. 1982; (24) Johnsson 1994; (25) Kanber et al. 1993; (26) Kirkham and Kanemasu 1983; (27) Lascano et al. 1994; (28) Laylock 1964; (29) Lopez-Castaneda and Richards 1994; (30) Mahalakshmi et al. 1994; (31) Oliva et al. 1994; (32) Power 1991; (33) Pruitt et al. 1984; (34) Rockström 1992; (35) Scott and Sudmeyer 1993; (36) Shih and Rahi 1984; (37) Shih and Snyder 1985; (38) Shih et al. 1983; (39) Shih 1988; (40) Stephens and Carr 1991; (41) Stewart et al. 1975; (42) Tanner 1981; (43) Thomas 1984; (44) Turner and McCauley 1983; (45) Waldren 1983; (46) Winter 1988; (47) Yadav et al. 1994; (48) Yao and Goué 1992; (49) Yates and Taylor 1986; (50) Bucks et al. 1984. For full citations, see Appendix 4.

Footnotes:

^a Yield data for individual crops were collected from Faostat (1997)

^b The WUE was calculated based on the total dry matter yield.

^c The mean WUE comes from only one article why the low and high values are the variations within that article.

^d The total water vapor flow from oil palm and coconuts was calculated as

$$\text{total water vapor flow (km}^3/\text{yr)} = \text{area harvested (km}^2\text{)} \times \text{ET (m) from palm stands}$$

The ET from palm stands is 1500 mm and for coconut it is 1320 (Jackson 1989). The low/high was assumed to be 1250 mm and 1750 mm (oil palm) and 1200 and 1500 mm (coconuts). The area of coconut production was collected from Faostat. For oil palms, the area harvested (the same area is also harvested for oil kernels and fruit) was calculated by

area harvested (ha/yr) = oil produced (Mg/yr)/production of oil (Mg/ha)

Palm oil production (6603778 Mg) was collected from Faostat. The production was assumed to be 1.75 Mg/ha (Mémento de l'Agronome 1984).

^e For vegetables that were produced as feed, the WUE was calculated based on the grain yield of that specific crop or subgroup, not the total biomass.

^f Spices is a small group with roughly 0.045% of the total global area harvested each year (Faostat 1997). Within this subgroup there is a large variation in species composition as well as in parts of plant used for production measurement. The WUE was therefore based on a qualified assumption of 1000 m³/Mg. The low was assumed to 800 m³/Mg and the high to 1200 m³/Mg. This is higher than the 500 m³/Mg that Postel et al. (1996) used as an average global WUE value. Because spices are often just a small part of a plant, the WUE will be higher.

* nes = not elsewhere specified or included (abbreviation from FAO Stat. 1997.)

APPENDIX 2

Total water vapor flow from forests/woodlands, wetlands, and grasslands, with data and references for calculation and classification of subgroups.

Biome	Subgroup	Climatic zone	Area ^a (10 ³ km ²)	nb	ET (mm/yr)			Water vapor flow (km ³ /yr)			References ^c
					Mean	Low	High	Mean	Low	High	
Forest	taiga	boreal	11,560	3	401	380	420	4636	4393	4855	
					420						L'Vovich (1979)
					403						Black et al. (1996)
					380						Frank and Inouye (1994)
	predominantly coniferous	temperate	3500	4	487	395	580	1705	1383	2030	
543										Frank and Inouye (1994)	
395										Tiktak and Bouten (1994)	
430										Running et al. (1989)	
					580						Yin (1993)
	predominantly deciduous	temperate	8500	4	729	588	964	6199	4998	8194	
588										Frank and Inouye (1994)	
620										Yin (1993)	
745										Luxmoore (1983)	
					964						Moran and O'Shaugnessy (1984)
	woodland/ woody savanna	temperate	5200	3	416	300	530	2165	1560	2756	

					300						Angell and Miller (1994)
					530						L'Vovich (1979)
					419						Joffre and Rambal (1993)
	dry/deciduous/seasonal	tropical/subtropical	7400	2	792	783	800	5857	5794	5920	
					783						San José et al. (1995)
					800						L'Vovich (1979)
	wet	tropical/subtropical	5300	3	1245	880	1493	6600	4664	7913	
					880						L'Vovich (1979)
					1363						Frank and Inouye (1994)
					1493						Leopoldo et al. (1995)
	savanna/woodland, dry	tropical/subtropical	12,700	2	882	870	894	11,201	11,049	11,354	
					870						L'Vovich (1979)
					894						Frank and Inouye (1994)
	wet	tropical/subtropical	1300	3	1267	1100	1500	1647	1430	1950	
					1100						L'Vovich (1979)
					1500						L'Vovich (1979)
					1200						L'Vovich (1979)
Subtotal			55,460					40,009	35,271	44,972	
Wetland	bog	boreal	651	3	221	200	260	144	130	169	Frank and Inouye (1994)
					202						
					200						Rouse (1982)
					260						L'Vovich (1979)
	bog	temperate	488	4	674	456	1020	329	223	498	
					456						Boeye and Verheyen (1992)
					490						Mitsch and Gosselink (1993)
					730						Gilvear et al. (1993)
					1020						Mitsch and Gosselink (1993)
	swamp	temperate	41	3	843	670	720	35	27	30	

					670						Mitsch and Gosselink (1993)
					1139						Gehrels and Mulamoottil (1990)
					720						Mitsch and Gosselink (1993)
	swamp	subtropical	16	5	1127	930	1277	18	15	20	
					930						Mitsch and Gosselink (1993)
					1032						Yin and Brook (1992)
					1317						Dolan et al. (1984)
					1080						Mitsch and Gosselink (1993)
					1277						Abtew (1996)
	swamp ^d	tropical	508	1	1656	1408	1904	841	715	967	Schaeffer-Novelli et al. (1990)
					1656						
Subtotal			1704					1366	1110	1684	
Grassland	cool grassland	temperate	6940	16	410	130	633	2843	900	4393	
					130						Branson et al. (1969)
					190						Sims et al. (1978)
					205						Liang et al. (1989)
					276						Bokhari and Singh (1974)
					339						Scott and Sudemyer (1993)
					413						Frank and Inouye (1994)
					417						Sims et al. (1978)
					422						Roberts and Roberts (1992)
					450						L'vovich (1979)
					450						Sims et al. (1978)
					450						Stephenson (1990)
					480						Bokhari and Singh (1974)

					530						Sims et al. (1978)
					571						Frank and Inouye (1994)
					600						Stephenson (1990)
					633						Bokhari and Singh (1974)
	warm and hot grassland ^e	tropical	17,300	7	599	403	862	10,356	6967	14,913	
					403						Le Houerou (1984)
					466						Lieth (1975)
					500						L'vovich (1979)
					596						Misra (1979)
					655						Carlson et al. (1990)
					708						Laurenroth (1979)
					862						Weltz and Blackburn (1995)
	montane grassland	temperate	650	4	655	430	951	426	280	618	
					430						Sims et al. (1978)
					440						Sims et al. (1978)
					799						Holdsworth and Mark (1990)
					951						Holdsworth and Mark (1990)
	montane grassland ^f	tropical	650	1	600	402	798	390	261	519	
					600						L'vovich (1979)
	dry shrubland	tropical	4000	2	270	225	315	1080	900	1260	
					225						Stephenson (1990)
					315						Stephenson (1990)
Subtotal			29,540					15,095	9308	21,702	

^a Surface areas for grasslands and forest/woodlands are based on Olson et al. (1983), and for wetlands on Matthews (1983), because total spatial coverage of wetlands corresponds roughly with Olson's database, whereas Matthews' has a finer classification of wetlands categories.

^b Here, *n* refers to the number of references.

^c For references, see Appendix 4.

^d Low/high values are based on a coefficient of variation of +/- 15%.

^e When annual precipitation $P < 600$ mm/yr, we assumed that $ET = P$ (i.e., that there is no blue water flow). This assumption is valid for dry grasslands on a large spatial scale (Le Houerou 1984). For grassland systems with $P > 600$ mm/yr, 20% runoff was assumed. These assumptions were made due to lack of data on ET from grasslands in tropical regions.

^f Low/high values are based on a coefficient of variation of $\pm 33\%$, which is the average standard deviation of the grassland subgroups with more than two references.

APPENDIX 3

Estimating evaporating surface runoff from croplands.

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.

Continent	Precipitation ^a	Surface runoff ^a	Runoff coefficient, continental scale	Runoff coefficient, field scale	Difference in surface runoff	Evaporating surface runoff (10.5% croplands ^b)
	km ³ /yr	km ³ /yr	%	%	km ³ /yr	km ³ /yr
Africa	20780	2480	12	20	1676	176
Asia	32140	9130	28	30	512	54
South America	29355	6450	22	25	889	94
Sum						324

^a Data from Lovich and White (1990).

^b The global cropland area is roughly 10.5% of the global terrestrial area.

APPENDIX 4

Cited literature in appendices.

Abtew, W. 1996. Evapotranspiration measurements and modelling for three wetland systems in south Florida. *Water Resources Bulletin* **32**: 465-473.

Ajtay, G. L., P. Ketner, and P. Duvigneaud. 1979. Pages 129-182 in B. Bolin, E. T. Degens, S. Kempe, and P. Ketner. *The global carbon cycle*. John Wiley, New York, New York, USA

Andersen, M. N., C. R. Jensen, and R. Lösch. 1992. The interaction effects of potassium and drought in field-grown barley. I. Yield, water-use efficiency and growth. *Acta Agriculturae Scandinavica* **42**: 34-44.

Angell, R. F., and R. F. Miller. 1994. Simulation of leaf conductance and transpiration in *Juniperus occidentalis*. *Forest Science* **40**: 5-17.

Armstrong, E. L., J. S. Pate, and D. Tennant. 1994. Water use and root growth in field pea. *Australian Journal of Plant Physiology* **21**: 517-532.

Ashley, D. A. 1983. Pages 389-422 in I. D. Teare and M. M. Peet, editors. *Crop-water relations*. John Wiley, New York, New York, USA.

Baker, R. E., A. B. Frank, and J. D. Berdahl. 1989. Cultivar and clonal differences for water-use efficiency and yield in four forage grasses. *Crop Science* **29**: 58-61.

Barros, L.C.G., and R. J. Hanks. 1993. Evapotranspiration and yield as affected by mulch and irrigation. *Agronomy Journal* **85**: 692-697.

Beech, D. F., and G. J. Leach.1989. Comparative growth, water-use, and yield of chickpea, safflower, and wheat in south-eastern Queensland. *Australian Journal of Experimental Agriculture***29**: 655-662.

Bhan, S., M. Balaraju, and V. Ram.1980. Water use, yield, and quality of rapeseed as influenced by spacing, irrigation and time of harvest when raised in a multiple-cropping system. *Indian Journal of Agricultural Science***50**: 760-763.

Black, C. C.1971. Ecological implications of dividing plants into groups with distinct photosynthetic production capabilities. *Advances in Ecological Research***7**:87-110.

Black, T. A., G. Denhartog, H. H. Neuman, P. D. Blanken, P. C. Yang, C. Russell, Z. Nestic, X. Lee, S. G. Chen, R. Staehler, M. D. Novak.1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. *Global Change Biology***2-3**:219-229.

Boeye, D., and R. F Verheyen.1992. The hydrological balance of a groundwater discharge fen. *Journal of Hydrology***137**: 149-163.

Bokhari, U. G., and J. S Singh.1975. Standing state and cycling of nitrogen in soil-vegetation components of prairie ecosystems. *Annual Botany***39**:273-285.

Bolger, T. P., and A. G. Matches.1990. Water-use efficiency and yield of safoin and alfalfa. *Crop Science***30**: 143-148.

Boote, K. J.1983. Pages 255-286 *in*l. D. Teare and M. M.Peet, editors. *Crop-water relations*.John Wiley, New York, New York, USA.

Branson, F. A, R. F. Millerand, and I. S. McQueen.1969. Plant communities and associated soil and water factors on shale-derived soils in northeastern Montana. *Ecology***51**:391-407.

Brown, S. C., P. J.Gregory, and A. Wahbi.1987. Pages 275-283 *in*J. P. Srivastava, E. Porceddu, E. Acevedo, and S. Varma, editors. *Drought tolerance in winter cereals*.John Wiley, Chichester, UK.

Bucks, D. A., F. S. Nakayama, and O. F. French.1984. Water management for guayule rubber production. *Transactions of the ASAE*.**27**:1763-1770.

Bucks, D. A., F. S.Nakayama, O. F. French, W. W. Legard, and W. L Alexander.1985. Irrigated guayule - production and water use relationships. *Agricultural Water Management***10**:95-102.

Carlson, D. H., T. L. Thurow, R. W. Knight, and R. K. Heitschmidt.1990. Effect on honey mesquite on the water balance of Texas Rolling Plains rangeland. *Journal of Range Management* **43**:491-496.

Dolan, T. J., A. J. Hermann, S. E. Bayley, and J. Zoltek.1984. Evapotranspiration of a Florida, U.S.A., freshwater wetland. *Journal of Hydrology***74**: 355-371.

Doorenbos, J., and A. H. Kassam.1979. *Yield response to water*.FAO Irrigation and Drainage Paper, Rome, Italy.

Entz, M. H., and D. B. Fowler.1991. Agronomic performance of winter versus spring wheat. *Agronomy Journal***83**:527-532.

FAO.1995. *World agriculture: towards 2010*.N. Alexandratos, editor. John Wiley, Chichester, UK.

Faostat.1997. Electronic database available on the internet <http://apps.fao.org>FAO, Statistics Division, Rome, Italy. [Data taken 09/26/97.]

Frank, D. A., and R. S. Inouye.1994. Temporal variation in actual evapotranspiration of terrestrial ecosystems: patterns and ecological implications. *Journal of Biogeography***21**:401-411.

Gascho, G. J., and S. F. Shih.1983. Pages 445-480 *in*l. D. Teare and M. M.Peet, editors. *Crop-water relations*. John Wiley, New York, New York, USA.

Gehrels, J., and G. Mulamoottil.1990. Hydrologic processes in a southern Ontario wetland. *Hydrobiologia***208**:221-234.

Gilvear, D. J., R. Andrews, J. H.Tellam, J. W. Lloyd, and D. N. Lerner.1993. Quantification of the water

balance and hydrogeological processes in the vicinity of a small groundwater-fed wetland, East Anglia, UK. *Journal of Hydrology***144**: 311-334.

Gleick, P. H. 1996. Basic water requirements for human activities: meeting basic needs. *Water International***21**:83-92.

Gregory, P. J. 1988. Pages 171-175 in Proceedings of a Conference on Dryland Farming, Amarillo/Bushland, Texas, August 1988. *Challenges in dryland agriculture: a global perspective*. Texas A & M University Press, Texas, USA.

Grimes, D. W., H. Yamada, and W. L. Dickens. 1969. Functions for cotton (*Gossypium hirsutum* L.) production from irrigation and nitrogen fertilization variables: I. Yield and evapotranspiration. *Agronomy Journal***61**: 769-773.

Hattendorf, M. J., M. S. Redselfs, B. Amos, L. R. Stone, and R. E Gwin, Jr. 1988. Comparative water use characteristics of six row crops. *Agronomy Journal***80**: 80-85

Hearn, A. B. 1980. Water relationships in cotton. *Outlook Agriculture***10**: 159-166.

Heichel, G. H. 1983. Pages 127-156 in D. Teare and M. M. Peet, editors. *Crop-water relations*. John Wiley, New York, New York, USA.

Heitholt, J. J. 1989. Water use efficiency and dry matter distribution in nitrogen and water-stressed winter wheat. *Agronomy Journal***81**: 464-469.

Hillel, D., and Y. Guron. 1973. Relation between evapotranspiration rate and maize yield. *Water Resources Research***9**: 743-748.

Holdsworth, D. K., and A. F. Mark. 1990. Water and nutrient input : output budgets. Effects of plant cover at seven sites in upland snow tussock grasslands of Eastern and Central Otago, New Zealand. *Journal of the Royal Society of New Zealand***20**: 1-24.

Imitiyaz, M., K. J. Kristensen, and V. Overgaard Mogensen. 1982. Influence of irrigation on water extraction, evapotranspiration, yield and water use efficiency of spring wheat and barley. *Acta Agriculturae Scandinavica***32**: 263-271.

Jackson, I. J. 1989. *Climate, water and agriculture in the tropics*. Longman Scientific and Technical, New York, New York, USA.

Joffre, R., and S. Rambal. 1993. How tree cover influences the water balance of Mediterranean rangelands. *Ecology***74**: 570-582.

Johnsson, R. C. 1994. Pages 71-78 in M. C. Heath, T. M. Hess, T. J. Hocking, D. K. L. Mackerran, and W. Stephens, editors. *Aspects of applied biology*. Volume 38. Association of Applied Biologists, Wellesbourne, UK

Kanber, R., A. Yazar, S. Önder, and H. Köksal. 1993. Irrigation response of pistachio (*Pistacia vera* L.). *Irrigation Science***14**: 7-14.

Kirkham, M. B., and Kanemasu. 1983. Pages 481-520 in D. Teare and M. M. Peet, editors. *Crop-water relations*. John Wiley, New York, New York, USA.

L'vovich, M. I. 1979. *World water resources and their future*. LithoCrafters Inc., Chelsea, UK.

L'vovich, M. I., and G. F. White. 1990. Use and transformation of terrestrial water systems. Pages 235-252 in B. L. Turner II, W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews, and W. B. Meyer, editors. *The Earth as transformed by human action*. Cambridge University Press, Cambridge, UK.

Lascano, R. J., R. L. Baumhart, S. K. Hicks, and J. L. Heilman. 1994. Soil and plant water evaporation from strip-tilled cotton: measurement and simulation. *Agronomy Journal***86**: 987-994.

Lauenroth, W. K. 1979. Pages 3-24 in N. R. French, editor. *Perspectives in grassland ecology*. Springer-Verlag, New York, New York, USA.

Laycock, D. H. 1964. An empirical correlation between weather and yearly tea yields in Malawi. *Tropical*

*Agriculture***41**:277-300.

Le Houerou, H. N.1984 Rain use efficiency: a unifying concept in arid-land ecology. *Journal of Arid Environments***7**:213-247.

Leopoldo, P. R., W. K. Franken, and N. A. V. Nova.1995. Real evapotranspiration through a tropical rain forest in central Amazonia as estimated by the water balance method. *Forest Ecology and Management***73**:185-195.

Liang, Y. M., D. L. Hazlett, and W. K. Laurenroth.1989. Biomass dynamics and water use efficiencies of five plant communities in the shortgrass steppe. *Oecologia* **80**:148-153.

Lieth, H.1975. Pages 203-216 in H. Lieth and R. H. Whittaker, editors. *Primary productivity of the biosphere*. Springer-Verlag, Berlin, Germany.

López-Castañeda, C., and R. A. Richards.1994. Variation in temperate cereals in rainfed environments. III. Water use and water-use efficiency. *Field Crops Research***39**:85-98.

Luxmoore, R. J.1983. Water budget of an eastern deciduous forest stand. *Journal of the Soil Science Society of America***47**:785-791.

Mahalakshmi, V. S. Grandos, I. Naji, S. Ceccarelli, and J.M. Peakock.1994. Pages 145-152 in M. C. Heath, T. M. Hess, T. J. Hocking, D. K. L. Mackerran, and W. Stephens, editors. *Aspects of applied biology*. Volume 38. Association of Applied Biologists, Wellesbourne, UK.

Matthews, E.1983. Global vegetation and land use: new high-resolution databases for climate studies. *Journal of Climate and Applied Meteorology***22**:474-487.

Mémento de l'Agrologue.1984. Ministère de la coopération et du développement, Paris, France.

Misra, R. C.1979. Pages 189-246 in R. T. Coupland, editor. *Grassland ecosystems of the world*. Cambridge University Press, Cambridge, UK

Mitch, W. J., and J. G. Gosselink.1983. *Wetlands*. Van Nostrand Reinhold, New York, New York, USA.

Moran, R. J., and P. J. O'Shaughnessy.1984. Determination of the evapotranspiration of *E. regnans* forested catchments using hydrological measurements. *Agricultural Water Management***8**:57-76.

Oliva, R. N., J. J. Steiner, and W. C. Young.1994. White clover seed production: I. Crop water requirements and irrigation timing. *Crop Science***34**:762-767.

Olson, J. S., J. A. Watts, and L. J. Allison.1983. *Carbon in live vegetation of major world ecosystems*. Oak Ridge National Laboratory, Environmental Science Division, Report ORNL-5862, Oak Ridge, Tennessee, USA.

Postel, S. L., G. C. Daily, and P. R. Ehlich.1996. Human appropriation of renewable fresh water. *Science***271**:785-788.

Power, J. F.1991. Growth characteristics of legume cover crops in a semiarid environment. *Soil Science Society of America Journal***55**:1659-1663.

Pruitt, W. O., E. Fereres, D. W. Henderson, and R. M Hagan.1984. Evapotranspiration losses of tomatoes under drip and furrow irrigation. *California Agriculture***38**:10-11.

Roberts, G., and A. M. Roberts.1992. Computing the water balance of a small agricultural catchment in southern England by consideration of different land-use types. II. Evaporative losses from different vegetation types. *Agricultural Water Management***21**:155-166.

Rockström, J.1992. *Water use efficiency in agriculture: How can it be improved in arid and semi-arid tropics?* Report Tema V, University of Linköping, Department of Water and Environmental Studies, Linköping.

Rouse, W. R.1982. The water balance of upland tundra in the Hudson Bay lowlands - measured and modelled. *Canadian Naturaliste***109**:457-467.

Running, S. W., R. R. Nemani, D. L. Peterson, L. E. Band, D. F. Potts, L. L. Pierce, and M. A.

Spanner.1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. *Ecology***70**: 1090-1101.

San-José, J. J., R. A. Montes, and A. Florentino.1995. Water flux through a semi-deciduous forest grove of the Orionocco savannas. *Oecologia***101**: 141-150.

Schaeffer-Novelli, Y., H. de SL. Mesquita, and G. Cintron-Molero.1990. The Cananeia Lagoon estuarine system, Sao Paulo, Brazil. *Estuaries***13**:193-203.

Scott P. R., and R. A Sudemyer.1993. Evapotranspiration from agricultural plant communities in the high rainfall zone of the southwest of Western Australia. *Journal of Hydrology***146**: 301-319.

Shih, S. F., G. S.Rahi, G. H. Snyder, D. S. Harrison, and A. G. Smajstrla.1983. Rice yield, biomass and leaf area related to evapotranspiration. *Transactions of the ASAE***26**:1458-1464.

Shih, S.F.1988 Sugarcane yield, biomass and water use efficiency. *Trans. ASAE***31**:142-148.

Shih, S. F., and G. S. Rahi.1984. Evapotranspiration of lettuce in relation to water table depth. *Transactions of the ASAE***27**: 1047-1080.

Shih, S. F., and G. H. Snyder.1985. Water table effects on pasture yield and evapotranspiration. *Transactoins of the ASAE***28**: 1573-1577.

Shuval, H.1996. *Sustainable water resources versus concepts for food security, water security, and water stress for arid countries.*CFWA workshop, Stockholm Environment Institute, New York, New York, USA.

Sims, P. L, J. S. Singh, and W. K. Laurenroth.1978. The structure and function of ten western North American grasslands. I. Abiotic and vegetational characteristics. *Journal of Ecology***66**: 251-280.

Stephens, W., and M. K. V. Carr.1991. Responses of tea (*Camellia sinensis*) to irrigation and fertilizer. II. Water use. *Experimental Agriculture***27**:193-210.

Stephenson, N. L.1990. Climatic control of vegetation distribution: the role of the water balance. *American Naturalist***135**:649-670.

Stewart, J. I., R. D. Misra, W. O. Pruitt, and R. M. Hagan.1975. Irrigating corn and grain sorghum with a deficient water supply. *Transactions of the ASAE***18**:270-280.

Tanner, C. B.1981. Transpiration efficiency of potato. *Agronomy Journal***73**:59-64.

Thomas, H.1994. Pages 41-46 inM. C. Heath, T. M. Hess, T. J. Hocking, D. K. L. Mackerran, and W. Stephens, editors. *Aspects of applied biology.*Volume 38. The Association of Applied Biologists, Wellesbourne, UK

Tiktak, A., and W. Bouten.1994. Soil water dynamics and long-term water balances of a Douglas-fir stand in the Netherlands. *Journal of Hydrology***156**: 265-283.

Turner, N. C., and G. N. McCauley.1983. Pages 307-350 inI. D. Teare and M. M.Peet, editors. *Crop-water relations.*John Wiley, New York, New York, USA.

Vitousek, P.M., P.R. Ehrlich, A.H. Ehrlich, and P.A. Matson, P.A.1986. Human appropriation of the products of photosynthesis. *BioScience***36**: 368 373.

Waldren, R. P.1983. Pages 187-212 inI. D. Teare and M. M.Peet, editors. *Crop-water relations.*John Wiley, New York, New York, USA.

Weltz, M. A., and W. H. Blackburn.1995. Water budget for south Texas rangelands. *Journal of Range Management***48**: 45-52.

Winter, S. R.1988. Influence of seasonal irrigation amount on sugarbeet yield and quality. *Journal of Sugarbeet Research***25**: 1-9.

WRI.1994. World resources, 1994-1995. Oxford University Press, Oxford, UK.

Yadav, S. K., K. Chander, and D. P. Singh.1994. Response of late-sown mustard (*Brassica juncea*) to

irrigation and nitrogen. *Journal of Agricultural Science* **123**:219-224.

Yao, N. R., and B. Goué.1992. Water use efficiency of a cassava crop as affected by soil water balance. *Agricultural Forest Meteorology***61**: 187-203.

Yates, R. A., and R. D. Taylor.1986. Water use efficiencies in relation to sugarcane yields. *Soil Use and Management***2**: 70-76.

Yin, X.1993. Variation in foliar nitrogen concentration by forest type and climatic gradients in North America. *Canadian Journal of Forest Research***23**: 1587-1602.

Yin, Z. Y., and G. A. Brook.1992. Evapotranspiration in the Okefenokee Swamp watershed: A comparison of temperature-based and water balance methods. *Journal of Hydrology***131**:293-312.

Address of Correspondent:

Carl Folke
Natural Resources Management
Department of Systems Ecology
Stockholm University
S-106 91 Stockholm, Sweden
and
Beijer International Institute of Ecological Economics
Royal Swedish Academy of Sciences
PO Box 50005, S-10405 Stockholm, Sweden
Phone: +46 8 164217
Fax: +46 8 158417
calle@system.ecology.su.se

*The copyright to this article passed from the Ecological Society of America to the Resilience Alliance on 1 January 2000.



[Home](#) | [Archives](#) | [About](#) | [Login](#) | [Submissions](#) | [Notify](#) | [Contact](#) | [Search](#)