THE IMPACT OF ANTHROPOGENIC GLOBAL LAND COVER TRANSFORMATION ON THE LAND-ATMOSPHERE FLUXES OF THE WATER AND CARBON CYCLES

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Dissertation submitted in partial fulfillment of
the requirements for the degree of Doctor of Philosophy
in the Department of Earth and Ocean Sciences
in the Graduate School of Duke University

2005

ABSTRACT

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Abstract

To an ever increasing extent humans are transforming large areas of the Earth through activities such as deforestation, urbanisation and agriculture (Houghton 1994, Vitousek et al. 1997, Sanderson et al. 2002) which can impact the water and carbon cycles, essential for our life on Earth (Claussen 2004). By altering surface aerodynamic, thermodynamic, radiative, hydrologic and vegetative properties, land cover change directly alters land surface fluxes of water (**e**vapo**t**ranspiration, ET) and carbon (**n**et **p**rimary **p**roductivity, NPP). Despite the pervasive human impact on the global hydrologic and carbon cycles, robust estimates of such human impact are lacking. The goal of this thesis is to further our knowledge on the extent of human impact on the planet by advancing our understanding of uncertainties of and improving the current statistics of global-scale human land cover change impact on the global water cycle and carbon cycle, and to make estimates of the net change in global annual NPP and ET, and, finally to identify the areas of greatest change in surface fluxes from land cover change on the earth.

In Chapter 1 I estimate the impact of land cover change on NPP with the use of recent NPP and land cover change, data, many of which were collected at global and continental scales. Monte Carlo techniques that incorporate known and estimated error in the parameters provide estimates of uncertainty. Results indicate that humans appropriate 10 to 55% of terrestrial photosynthesis products. This broad range reflects uncertainty in key parameters and makes it difficult to ascertain whether we are approaching crisis

levels in our use of the planet's resources. Improved estimates will require high-resolution global measures within agricultural lands and tropical forests.

In Chapter 2, I present data on land cover change and regional and local estimates of ET to estimate human impact on land cover and ET, and resulting changes in the annual fluxes of ET and NPP. I show that by occupying 41 percent of all land, where over half of **t**errestrial **ET** (TET) occurs, humanity is slowing down the global water and carbon cycles, reducing annual ET and NPP on average by –3.8 and –6.2 percent respectively, although uncertainty in these estimates is high. This change is small compared with changes from individual land conversion components that cancel out in the sum. Yet results indicate that land cover change alters ET to a similar extent as is predicted for future climate change scenarios (Arora 2001). The appropriation calculations show that limits to resources will be reached in the next 50 years if humans do not use these resources more efficiently.

Global-scale summaries mask potentially important regional patterns of altered hydrology from land cover change. In Chapter 3 I investigate global patterns in change in annual ET from land cover change by applying the observational ET database to a series of adapted global land cover maps, using **G**eographic **I**nformation **S**ystems (GIS). I characterise land cover change by assembling and modifying existing global-scale maps of potential land cover, the land cover expected in the present climate had no human intervention occurred (“potential”), and of the present extent of anthropogenically-transformed agricultural, grazing, urban and inundated (reservoirs) land. By application of the global data base of annual ET estimates for discrete land covers, I estimate how the current extent of land cover change is altering global ET, and produce a global-scale map which highlights 9 “hotspots”, regions with the greatest change in annual ET. There are four “hotspots” with large increase in ET from irrigated agriculture (central USA, Aral Sea basin, India and Pakistan, and southwest Australia) where irrigated agriculture has replaced drylands. All of these areas have been previously identified for a high potential for water shortages. There are four hotspots with extensive decrease in ET (Central America, and Northern South America, Europe, central and south-eastern USA, sub-Saharan Africa, and Southeast Asia) where there have been large areas of forest converted to grazing, non-irrigated agricultural lands or built-up lands. The hotspots do not necessarily correspond with the areas with the most extensively modified land cover (Figure 3.2a), because some land cover changes tend to alter ET more strongly than others. The results of the study provide information to scientists, governments, and international organizations to aid the identification of the areas in the globe that are undergoing a water crisis that may be caused or exacerbated by land cover change; they allow us to identify regions where human modification of the landscape might be expected to alter precipitation patterns.

Taken together, the data presented in this thesis advance the field of global change by assembling and analysing a comprehensive database of land-atmosphere fluxes for the global water and carbon cycles. The uncertainty analysis work provides a solid framework for scientists in a range of disciplines to build upon.

Table of Contents

Abstract ... iv

Table of Contents ... vii

List of Tables ... ix

List of Figures ... xiii

Glossary and Abbreviations ... xv

Acknowledgements ... xxv

Introduction ... 1

Chapter 1. Human Appropriation of Photosynthesis Products ... 8

Chapter 2. Quantification of land cover change impact on global evapotranspiration and net primary productivity ... 17

- 2.1 Introduction ... 17
- 2.2 Methods ... 19
- 2.3 Results and Conclusions ... 23

Chapter 3. Distribution of Evapotranspiration Change from Global Anthropogenic Land Cover Change ... 33

- 3.1 Introduction ... 33
- 3.2 Land Cover Mapping ... 36
- 3.3 Database and Estimated Fields of ET ... 38
- 3.4 Change in ET with Land Cover Change (m/yr) ... 46
- 3.5 Change in ET volume ... 53
- 3.6 Limitations and Conclusions ... 63

Appendix A. Database of Land Cover Area Estimates ... 67

Appendix B. Database of Biomass Estimates 71

Appendix C. Estimates of Net Primary Productivity 79

Appendix D. Estimates of Proportions of Biomass Transfer 84

Appendix E. Estimates of Annual Actual Evapotranspiration 88

Appendix F. Estimates of Other Variables 131

Appendix G. Land Cover Data Sets 133

- G1. Agriculture 133
- G1a. Irrigated Agriculture 134
- G2. Built-Up Lands 135
- G3. Inundated Land (Reservoirs) 135
- G4. Grazing Land 136
- G5. Potential Vegetation 136
- G6. Wetlands 137

Appendix H. Maps of Kriged ET 142

Bibliography 147

Biography 212

List of Tables

Chapter 1

1.1 Description of variables in the formula used with updated estimates…......... 10

Chapter 2

2.1 Description of variables in the formulae…………………………….................24

2.2 Impact of land cover transformation on terrestrial fluxes……………………...26

Chapter 3

3.1 Land cover classification scheme for ET database, and corresponding land cover map sources.….. 39

3.2 Annual actual ET estimates for discrete land covers derived from kriging of point estimates …….. 44

3.3 Global average change in ET from potential vegetation classes to anthropogenic land covers…... 50

3.4 Estimates of local ET change from land cover change from the literature……51

3.5 Components driving changes to ET from land cover change………………….52

3.6 Change in ET m^3/yr from anthropogenic land cover change.….......................54

Appendix A

A.1 Global agricultural area……...67

A.2 Global annual anthropogenically-burned area.…….. 68

A.3 Global built-up or human occupied area.…...68

A.4 Global grazing land area.…... 68

A.5 Global impounded water (reservoir) area.……... 68

A.6 Global tree plantation area…….. 69

A.7 Area of forest permanently cleared for population increase and colonisation... 69

A.8 Area of forest converted to grazing……... 69

A.9 Area of savannah…….. 70

A.10 Area cleared in tropical virgin forests by shifting cultivation……..…............. 70

Appendix B

B.1 Biomass of permanently cleared forest areas.. 71

B.2 Biomass of savannah……..73

B.3 Biomass of above-ground grasses in burned savannah……...............................75

B.4 Biomass of secondary tropical forest…….. 75

B.5 Biomass of tropical forests…….. 76

Appendix C

C.1 Productivity of agricultural lands……………………………...………… 79

C.2 Productivity of lands converted to pasture……………………………….…… 80

C.3 Productivity of built-up lands…………………………………………….…… 81

C.4 Productivity of tree plantations………………………………...………… 81

C.5 NPP of firewood……... 82

C.6 NPP eaten by livestock……………………………………………………82

C.7 Total terrestrial net primary productivity…….. 83

Appendix D

D.1 Proportion of forest biomass relative to merchantable fraction……................. 84

D.2 Proportion of firewood supply met by land clearing and shifting cultivation… 85

D.3 Proportion of burning on natural grazing lands... 85
D.4 Proportion of productive human-occupied lands... 85
D.5 Proportion of natural pasture grazed by livestock... 85
D.6 Proportion of NPP eaten by livestock coming from natural lands................ 85
D.7 Proportion of firewood harvested but not used every year........................ 85
D.8 Proportion of savannah burned annually.. 86
D.9 Proportion of shifting cultivation in savannas.. 86
D.10 Proportion of shifting cultivation in secondary tropical forest.................. 86
D.11 Proportion of wood that humans use of tree plantation origin.................. 87

Appendix E

E.1 Annual evapotranspiration of agricultural areas... 89
E.2 Annual evapotranspiration of burned areas.. 92
E.3 Annual evapotranspiration of barren or sparsely vegetated lands............... 92
E.4 Annual evapotranspiration of human built-up areas..................................... 93
E.5 Annual evapotranspiration of natural forest areas.. 95
E.6 Annual evapotranspiration of natural grassland.. 110
E.7 Annual evapotranspiration of grazing areas.. 116
E.8 Annual evapotranspiration of impounded areas (reservoirs)...................... 119
E.9 Annual evapotranspiration of tree plantations.. 123
E.10 Annual evapotranspiration of wetlands... 126
E.11 Global annual terrestrial evapotranspiration.. 128

Appendix F

F.1 Clearing rate of shifting cultivation……... 130

F.2 Population that uses shifting agriculture…………………………..……… 130

F.3 Density of fibre / construction wood……………………………………… 130

F.4 Volume of forest harvest used for construction and fibre in temperate areas.. 131

F.5 Volume of forest harvest used for construction and fibre in tropical areas….. 131

List of Figures

Chapter 1

1.1 Template used to estimate HTNPP…………………………………….………… 9

1.2 Histogram of estimate of HTNPP allowing all parameters in the formula to vary with limits set by their estimated uncertainty……………………………….… 12

1.3 Sensitivity analysis showing key independent parameters that strongly influence uncertainty in the estimate of HTNPP……………………………………….……15

Chapter 2

2.1 Sensitivity analysis showing key parameters that strongly influence uncertainty……………………………………...26

2.2 Human occupied land cover, terrestrial net primary productivity (NPP) and terrestrial ET ($HOTET_{HSR}$) …………………………………….…................... 27

2.3a. Mean contributions of individual anthropogenic land covers to change in global annual terrestrial ET and NPP…………………………………….............. 29

2.3b. Mean contribution of discrete land transformations to change in global annual terrestrial ET…………………………………….. 29

Chapter 3

3.1 Relative areas of major anthropogenic land covers ……………………..……. 33

3.2 Distribution of estimates of actual annual ET for discrete land covers, and the extent of major anthropogenic land covers…………………………….……………41

3.3 Gridded annual ET estimates……………………………………………..45

3.4 Change in ET (m/yr) for conversion to individual anthropogenic land covers...49

3.5 Change in volume of annual ET from potential to anthropogenic land cover…57

3.6 Capacity of watersheds or regions to buffer ET changes……………………... 60

3.7 Basins in hotspot areas……………………... 61

Appendix G.

G.1a Global irrigated agriculture……………………………………………..……... 138

G.1b Global non-irrigated agriculture…………………………………………... 138

G.2 Global built-up areas……………………………………............................ 139

G.3 Global reservoirs……………………………….................................139

G.4 Global grazing Lands………………………………..........................140

G.5 Potential vegetation, wetlands added……………………………………...140

Appendix H

H.1 Point ET estimates and kriged global field of agriculture…………………….142

H.2 Point ET estimates and kriged global field of urban and built-up areas…..… 142

H.3 Point ET estimates and kriged global field of reservoirs……………………..143

H.4 Point ET estimates and kriged global field of grazing………………………..143

H.5 Point ET estimates and kriged global field of forests……………………….. 144

H.6 Point ET estimates and kriged global field of grassland…………………… 144

H.7 Point ET estimates and kriged global field of barren land………………….. 145

H.8 Point ET estimates and kriged global field of wetland……………………… 145

Glossary and Abbreviations

Agricultural Lands

Here, irrigated or non-irrigated cultivated lands that do not include grazing lands.

Albedo

The ratio of the light reflected by a body to the light received by it. Albedo values range from 0 (pitch black) to 1 (perfect reflector).

Anthropogenic Land Cover (HLC)

Transformed landscapes resulting from human activities, including agriculture, built-up areas and urban land, reservoirs, and grazing land.

Appropriation (as employed here, and first used by (Vitousek et al. 1986))

A measure of the amount of the flux or mass, most commonly ET or NPP, touched (but not necessarily altered) by human activity (Vitousek et al. 1986, Postel et al. 1996, Rojstaczer et al. 2001, Imhoff et al. 2004). Others (Haberl et al. 2001, Krausmann et al. 2003) use appropriation defined as a change in flux from human land cover change; here, interchangeably used with “occupancy”.

Atmospheric General Circulation Model (AGCM)

Numerical representation of the atmosphere and its phenomena over the entire Earth, using the equations of motion and including radiation, photochemistry, and the transfer of heat, water vapour, and momentum.

Bowen Ratio

The ratio of sensible to latent heat fluxes from the earth's surface up into the air.

Built-Up Land (or Urban Land)

Regions where the ecosystem has been significantly transformed into a human-devised habitat filled with office buildings, housing developments, and strip malls.

Eddy Covariance

A method of estimating evaporation and other atmospheric fluxes by measuring short-period fluctuations in the vertical wind velocity and water vapour at some arbitrary levels.

Evapotranspiration (ET)

The process by which water is returned to the atmosphere, and is the sum of evaporation of water from the soil or water surface and transpiration by plants. It is equivalent to the latent heat turbulent energy flux.

FAO (United Nations Food and Agricultural Organisation)	An international organisation which seeks to raise levels of nutrition, improve agricultural productivity, better the lives of rural populations and contribute to the growth of the world economy.
FLUXNET	A global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapour, and energy between terrestrial ecosystem and atmosphere.
Fossil-Water Irrigation	Irrigation using water from non-renewable groundwater resources (fossil water).
Global Terrestrial Observing System (GTOS)	A programme for observations, modelling, and analysis of terrestrial ecosystems to support sustainable development; facilitates access to information on terrestrial ecosystems so that researchers and policy makers can detect and manage global and regional environmental change.

Geographic Information Systems (GIS)

A system of computer software, hardware and data, and personnel to help manipulate, analyze and present information that is tied to a spatial location.

Grazing Land

In this study grazing land is defined as grasslands and shrublands used for grazing by livestock.

Grid Cell

A discreetly uniform unit that represents a portion of the Earth, such as a sq. meter or sq. mile, Each grid cell has a value that corresponds to the feature or characteristic at the site such as a soil type, census tract or vegetation class (GIS_Development 2005).

Hotspot

Here, area of risk for change in ET, for either precipitation or discharge impacts. Defined as areas of large change in ET, in regions with reduced ability to buffer the change.

Human Appropriated or Occupied Net Primary Productivity (HANPP/HTNPP)

Terrestrial net primary productivity that is appropriated for human purposes, as a percent of total annual terrestrial flux.

Human Appropriated or Occupied Terrestrial Evapotranspiration (HATET/HOTET)

Terrestrial evapotranspiration that is appropriated for human purposes, as a percent of total annual terrestrial flux.

HΔTET

The net change in terrestrial evapotranspiration caused by direct anthropogenic land cover change, as a percentage of its total annual terrestrial flux.

HΔTNPP

The net change in terrestrial net primary productivity caused by direct anthropogenic land cover change, as a percentage of its total annual terrestrial flux.

International Geosphere Biosphere Programme (IGBP)

An international scientific research programme that addresses international scientific questions and integrating scientific activities on global change.

Interception

Gross rainfall intercepted by leaves or litter and evaporated directly back to the atmosphere. Interception amount is dependent on the type of vegetation and on the intensity, duration, frequency and form of precipitation.

Irrigated Agriculture

Agriculture with controlled applications of water to supplement the rainfall. There are three main classes of irrigated agriculture: mountain-edge irrigation (Northern Italy from the Alps, Punjab and Uttar Pradesh from the Himalaya, central Chile from the Andes, and in Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan from the Tibetan plateau region), valley-bottom river diversions (San Joaquin Valley, USA, diverted from the Colorado River, the Nile River valley, and the Blue Nile), and “fossil water” irrigation, where water is introduced into the water cycle from ancient aquifer water (eg., Ogallala Aquifer, Central USA (Rosenberg et al. 1999), and central-pivot irrigation in Saudi Arabia).

Land Use

A series of management operations/actions on land, carried out by humans, with the intention to obtain products and/or benefits through using land resources (DeBie 2000).

Land Cover

The observed biophysical cover of the Earth's surface (FAO 2000).

Land Surface Model (LSM)

A set of equations which simulate land surface water and energy fluxes. Atmospheric and terrestrial input data are required for the equations.

Leaf Area Index (LAI)

The area of foliage per unit area of ground. Conventionally this refers to the ratio of the area of the upper side of the leaves in a canopy projected onto a flat surface to the area of the surface under the canopy.

Kriging

A geostatistical method of interpolating point data to a prediction surface that is based on statistical models that include autocorrelation (the statistical relationship among the measured points). Because of this, it can provide some measure of the certainty or accuracy of the predictions.

Miami Model

A global model used to examine the role of the terrestrial biosphere in the global C cycle, using a straightforward method where NPP is derived from climate data for each vegetation type (Lieth 1973).

Moisture Recycling

The process by which part of the precipitated water which evaporated from a given area contributes to the precipitation over the same area; also referred to as precipitation recycling or locally-derived precipitation

Monte Carlo Simulation

An analytical technique for solving a problem by performing a large number of trail runs, called simulations, and inferring a solution from the collective results of the trial runs. A method for calculating the probability distribution of possible outcomes.

Net Primary Productivity (NPP)

The net flux of carbon from the atmosphere into green plants per unit time. NPP refers to a rate process, i.e., the amount of vegetable matter produced (net primary production) per day, week, or year. However, the terms *net primary productivity* and *net primary production* are sometimes used rather liberally and interchangeably, and some scientists still tend to confuse *productivity* with *standing biomass* or *standing crop*. NPP is a fundamental ecological variable, not only because it measures the energy input to the biosphere and terrestrial carbon dioxide assimilation, but also because of its significance in indicating the condition of the land surface area and status of a wide range of ecological processes (ORNL 2005).

Potential Land Cover (PLC)

The land cover that would be present under present day climate conditions had there not been human alteration of the land

Reservoirs or Inundated Land

Here, an anthropogenic lake or basin created for the storage, regulation, and control of water, usually by construction of a dam.

Risk Assessment

An appraisal of the hazard of an event to take place, that then to looks at the consequence of the event if it took place. The combination of hazard and consequence will result in a risk assessment.

Spatial Autocorrelation

The statistical property describing the spatial interdependence of a variable. If a variable is spatially autocorrelated, measurements taken close together tend to be more similar than those taken far apart. Spatial autocorrelation is quantified in a semivariogram.

Surface Roughness

The geometric characteristic of a surface associated with its efficiency as a momentum sink for turbulent flow, due to the generation of drag forces and increased vertical wind shear (Stull 1988).

Terrestrial Evapotranspiration (TET)

The total amount of evapotranspiration that flows from global land surfaces.

Transpiration

The process by which water in plants is transferred to the atmosphere in the form of water vapour. The amount of transpiration is controlled by the physiological characteristics of the vegetation, with the majority of transpiration occurring through the stomates, the small pores in the leaf epidermis.

Tree Plantations

Here, defined as deforested areas and secondary forests resulting from clearcutting, and include forests that have been managed (thinned, clearcut) within the past 40 years for tropical forests and 50 years for boreal forests.

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Introduction

Land cover change is one of the most visible ways humans are impact the planet; whether through removing forests for suburban housing, or flooding deserts for water reservoirs, or creating golf courses in the desert. As the human population and economy continue to expand, we are changing ever more of the limited surface of our planet. This study examines the impact of land cover change on the global water and energy cycles through the variables net primary productivity (NPP) and evapotranspiration (ET) – the land-atmosphere fluxes of the global carbon and water cycles, which are highly connected to land cover.

This work began in 2000, when my supervisor, Stuart Rojstaczer, asked me to revisit the seminal work of Postel and coworkers that estimated humans are appropriating 26% of total terrestrial ET (Postel et al. 1996). Their study was pioneering in its assessment of the impact of land cover change on the global water cycle, and this statistic has been frequently used by the scientific and international governing community as a demonstration of the extent of human impact on the global water cycle from anthropogenic land cover change, often used as an indication that humans are reducing total terrestrial ET.

My first investigations into this statistic revealed that the Postel et al. (1996) estimate was drawn from a previous estimate that humans appropriate 32% of global terrestrial net primary productivity (Vitousek et al. 1986)[1]. Therefore, to understand the Postel statistic it was necessary first to understand the (Vitousek et al. 1986) statistic. The Vitousek et al. (1986) study also has been popular as an indicator of human impact

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[1] their intermediate statistic

on the biosphere and the carbon cycle, and is used to show that human activity has led to a reduction in global biomass.

The (Vitousek et al. 1986) estimate of appropriated NPP was made possible by previous estimates of NPP for discrete land covers. There have been two periods when scientists have given great attention to the NPP for discrete land cover types. The first was in the late 1960s and early 1970s where for the first time, using the Miami model, Helmut Lieth estimated characteristic NPP fluxes for the major ecosystems of the world by using point estimates and using mapping techniques to extrapolate the point estimates to the biomes (Lieth 1972). Leith's work was furthered by Olson (Olson 1975), and Atjay and coworkers (Ajtay et al. 1979); these pioneering initiatives on the carbon cycle were key early attempts to understand how humans may be causing climate change by altering the global carbon cycle. Twenty years later, as research efforts into global climate change were gaining force, major research initiatives were put into modelling of the global carbon cycle. Remarkably, the estimates of mean NPP fluxes for the global biomes were close to those of Leith, Olson, and Atjay from twenty years earlier. The strength of Vitousek *et al.*'s work is that it was one of the first studies to assemble the emerging wealth of ecological data into a statistic to document the extent of human impact on the biosphere – a statistic to which they applied the term "appropriation".

While examining the (Vitousek et al. 1986) intermediate statistic I uncovered three issues: 1) the method of calculation was not transparent and quick to determine, nor was the meaning of the statistic; 2) the estimate needed to be updated, because the data were from work published in the 1960s and 1970s, particularly given the recent proliferation of

NPP and land cover change data; and finally, 3) as for many global statistics, the uncertainty was not estimated.

Thus began the first phase of this project, covered in Chapter 1, with the aim to rectify these problems related to the Vitousek et al. (1986) statistic. I first traced the variables that were used to calculate appropriated NPP back to their primary data source, and then assigned the primary source data a parameter name and abbreviation. These parameters range in type from NPP, biomass, area of human activity, and harvesting data. I also discovered that in the original manuscript the estimate of annual agriculture production (and used in Vitousek et al., 1986) was exchanged later with an estimate of wetland NPP, and that this error was propagated in the literature (eg., by (Olson 1975) and (Atjay et al. 1979)). Then, armed with the suite of parameters used to calculate the NPP statistic, I then sought all available published estimates for each parameter, a task which began the creation of the Land Cover and Land-Atmosphere Flux database, as presented in the appendices of this thesis.

It was important to elucidate the meaning of appropriation as used by Vitousek and colleagues because appropriation statistics have become fashionable and politically popular, and the meaning of "appropriation" is inconsistently defined. I extracted the exact calculations by interpreting several pages of Vitousek et al. (1986) text from secondary citations, and I reinterpreted the meaning of their statistic: that appropriation is the flux of NPP flowing through land impacted by humans (also used by (Vitousek et al. 1986, Postel et al. 1996, Rojstaczer et al. 2001, Imhoff et al. 2004)), and is therefore useful to assess the issue of biophysical / environmental limits to the human enterprise. Appropriation has also been defined in the literature (Haberl et al. 2001, Krausmann et al.

2003) to be a change in flux from human land cover change, a very different meaning with different applications, adding to the confusion regarding the meaning of appropriation.

By recalculating the NPP appropriation equation using the revised value of each variable, I found that the updated mean estimate of appropriated NPP was almost identical to that calculated 15 years earlier, despite the wealth of new data on NPP and area estimates. Upward revisions of some appropriations were balanced with downward revisions in others.

Yet, as with any global estimate of biophysical attributes, the statistic is highly uncertain. By using Monte Carlo simulations, I estimated the statistic to have a wide standard deviation (22% of terrestrial NPP). By estimating uncertainty, this paper represents a distinct advancement over many other global environmental assessment papers. The analysis also explicitly provides directions for future data acquisition that will help us gain a better and more precise understanding of human impact, as it identifies which variables contribute the most uncertainty to the statistic.

In Chapter 2, I turn my focus back to the Postel *et al.*, 1996 and their estimate of appropriated ET, now that a major part of the calculation, from (Vitousek et al. 1986), has been clarified and updated. As in the paper by Vitousek and colleagues, the equation used to estimate the statistic was not identified, and I discovered a serious error in the equation behind the appropriated ET statistic. Because the conversion of appropriated NPP (HANPP)(Vitousek et al. 1986) to TET by the global scale relation that follows (HANPP*(TET/TNPP))/(TET), and the ET components cancel out of the equation; this statistic is not about ET at all.

Postel and colleagues had to rely on appropriated NPP and a global-scale water use efficiency to estimate appropriated ET because there were no equivalent estimates for characteristic ET for the suite of global land cover types, such as had been done for NPP by Leith and colleagues. For example, there were no available estimates of average annual ET for urban lands, or for forest or grassland types across the globe.

With the aim correcting this error in the appropriated ET equation, I began assembling estimates of annual actual ET from over the globe, through literature searches, and direct contact with scientists. In the end I assembled over 1000 estimates of ET, providing the first quantification of ET for the range of different land cover types. Armed with the new ET data, I recalculated appropriated ET and found it to be over twice as large as previously thought, and like the estimate of appropriated NPP, the estimate was highly uncertain.

Given the context of rapid population and economic growth, the appropriation statistics from Chapters 1 and 2 highlight that there are limits to the earth's resources, and that we are approaching those limits. However, both statistics are uncertain, and if these statistics continue to be used to monitor the state of the environment, it is strongly recommended that work is done to reduce the uncertainty of the variables, guided by the results derived from the sensitivity analysis.

The Postel appropriation statistic has been widely cited (over 162 citations (ISI 2005)) for explanations of droughts and water crises, yet my work shows that this appropriation statistic does not inform us on how ET has changed. Yet the question remains - how is ET being changed from global land cover change? By using the database of ET estimates and of land cover change, I was able to make the first investigation of changed global ET, finding that humans are reducing ET by approximately 4% of total terrestrial ET, yet that it is highly uncertain.

It is clear that the 1-D approach used in Chapter 2 to calculate change in ET can be further expanded to 2 dimensions, by incorporating map-based geospatial analysis techniques. Such an approach has only recently become possible; advances in remote sensing have produced maps of individual anthropogenic land cover types, such as reservoirs, urban land, agriculture, irrigated agriculture, and grazing land.

Remarkably, the 2-D estimate of change in ET estimated in Chapter 3 (-4.1%) is almost the same as that from the 1-D estimate in Chapter 2 (-3.8%). Further, when the changed ET estimate is converted to changed NPP (-6.2%), using water use efficiencies from our database, we arrive at essentially the same estimate of changed NPP as was produced by an independent modelling study (-5%) (DeFries et al. 1999).

In Chapter 3 by assembling maps of potential vegetation and anthropogenic land covers, and by estimating characteristic global fields of ET for each land cover type, I make the first global map of current altered annual ET from land cover change. An added advantage of the map-based approach is that I can define “hotspots” where ET is most extensively altered. These predicted changes are testable in the field, laying fundamental groundwork for understanding how human activities are altering the global water cycle.

Chapters 2 and 3 break ground in attributing changes in ET to individual land cover conversions, and I explore these conversions by making a first global summary of the mechanisms behind these changes, and introduce a speculative model of how different landscapes can buffer changes to ET.

The research in all three chapters encompasses many different communities, including political, economic, global climate modelling, conservation ecology, and land surface hydrology. My recent work with global climate modellers in Paris, France has exposed me to the inner-workings of global climate and land surface models, and this experience has furthered my appreciation of the advantages of the simple accounting approaches used in this thesis. The strength of accounting approaches is that they are very transparent, and assumptions are easily identified if the equations behind the calculations are presented. In contrast, the complexity of global land surface and climate models is very high, making it very difficult to document all of the assumptions in the calculations, and I have found that some key assumptions with respect to land cover representation are hidden within lengthy model code.

It is hoped that these simple data-intensive accounting approaches will continue to be used to keep track of how humans are impacting the earth, through repeated updates, and that they will continue to be useful in providing an independent check to modelling studies. Together, modelling and accounting of observational data like that done here will provide a more comprehensive and clear path towards understanding anthropogenic global change.

Chapters 1 and 2 were collaborative work. Shannon Sterling did all aspects of the research and manuscript preparation except for the following: Stuart Rojstaczer (SR) came up with the idea to investigate the Postel et al., 1996 paper, to characterise the uncertainty of the statistic, and to use the Bayesian approach. Nathan Moore created the first draft of the C++ model to run the uncertainty simulations, which was subsequently modified by SR and Shannon Sterling.

Chapter 1. Human Appropriation of Photosynthesis Products

Human use of photosynthesis products is pervasive, including direct use of plants for food and fiber as well as indirect use from grazing by domesticated animals. Population increases have led to speculation and estimates that the human footprint on the biosphere, in terms of the use of both plants and fresh water, is approaching the limit of planet sustainability (Vitousek et al. 1986, Postel et al. 1996, Haberl 1997, Vitousek et al. 1997, Tilman 1999). A key measure of human impact on the biosphere and hydrosphere is human use of terrestrial net primary production (TNPP), which represents the net energy (production minus respiration) created by carbon fixation on land. Previous estimates of global human appropriation of this biological resource (HTNPP) - which governs the total amount of food available on Earth - and its surrogates (Houghton et al. 1985, Vitousek et al. 1986, Wright 1990, Pimentel and Pimentel 1996) have used mean estimates of parameters that were derived from limited, small-scale field studies. Here I incorporate contemporary data, many of which are satellite-based, to estimate HTNPP, and quantify the uncertainty in our knowledge of HTNPP.

HTNPP represents the combined effects of direct human use and use by human-altered ecosystems[2]. I adopted the method of Vitousek *et al.* (1986) to estimate HTNPP

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[2] Here I use the "intermediate calculation" of Vitousek *et al.* (Vitousek et al. 1986), which includes all TNPP appropriated by humans (indirectly or directly) and by human-altered ecosystems:

$$\Sigma(\mathrm{HTNPP}) = (A_{ag} \times PR_{ag}) + (A_{gcp} \times PR_{gcp}) + (NPP_{lse} \times P_{lse/nl} \times P_{lgrp/gp}) + (A_s \times P_{sh} \times B_{sh} \times P_{gbnl}) + (A_{tp} \times PR_{tp}) - P_{tp} \times \{ NPP_{fwd} + P_{fb/mf} \times [(V_{fhct} \times \rho_w) + (V_{fhctr} \times \rho_w)] + (NPP_{fwd} \times P_{nhfwd}) \} + (\{ [(V_{fhct} \times \rho_w) + (V_{fhctr} \times \rho_w)] \times P_{fb/mf} \} - [(V_{fhct} \times \rho_w) + (V_{fhctr} \times \rho_w)]) + (POP_{scs} \times CR_{sc} \times P_{scstrf} \times B_{strf}) + (POP_{sc} \times CR_{sc} \times P_{scs} \times B_{scs}) + (A_{sctrf} \times B_{trf}) + (A_{fc} \times B_{fcs}) - (NPP_{fwd} \times P_{fwd/lc}) + (V_{fhct} \times \rho_w) + (V_{fhctr} \times \rho_w) + NPP_{fwd} + (A_{ho} \times P_{ho} \times PR_{ho})$$

The "low calculation" of Vitousek *et*

(Table 1.1 and Figure 1.1), which uses global averages and sums the influences of agriculture, human-occupied lands, grazing, and forestry. To estimate HTNPP, I use available global-scale primary- source data in the literature[3]. I do not include studies earlier than 1990 for parameters with large temporal variability (e.g., parameters dependent on areas or populations). I also remove estimates that appeared to be highly anomalous (more than two standard deviations from the other estimates).

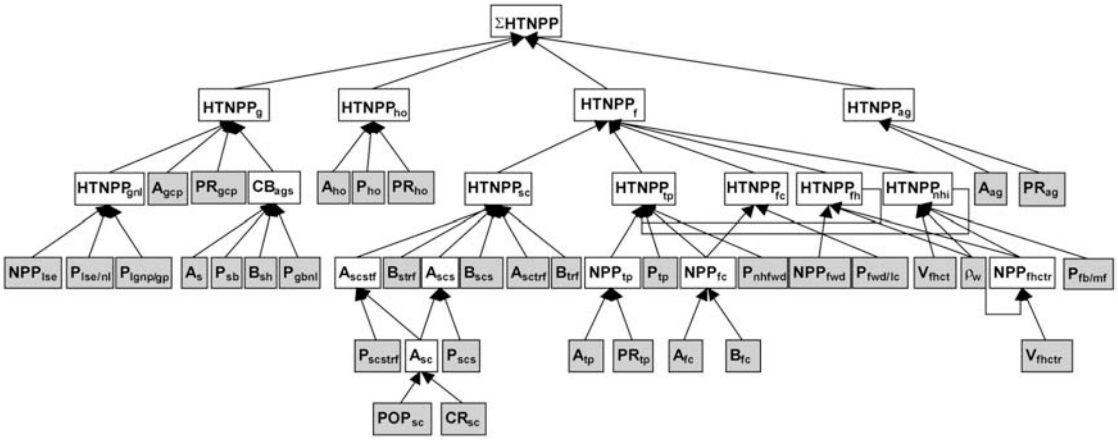

Figure 1.1. Template used to estimate HTNPP. The formula on which the template is based is the intermediate calculation of Vitousek *et al*. (Vitousek et al. 1986). Gray boxes represent independent parameters and are defined in Table 1.1. White boxes represent dependent parameters and are intermediate or final calculations. Abbreviations: *HTNPP*, co-opted terrestrial *NPP*; *A*, area; *CB*, co-opted biomass. Subscripts: *g*, livestock grazing; *ho*, human- occupied lands; *f*, forests; *ag*, agriculture; *gnl*, livestock grazing on natural lands; *ags*, burning in savannahs; *sc*, shifting cultivation; *tp*, tree plantation; *fc*, forest clearing (land use change); *fh*, industrial forest harvesting; *nhi*, not harvested but affected industrial forest; *scstrf*, shifting cultivation in secondary tropical forests; *scs*, shifting cultivation in savannahs; *fhctr*, industrial forest harvesting in tropical forests.

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al. (Vitousek et al. 1986), because it deals only with direct consumption, by design yields an unrealistically low assessment of human impact. The "high calculation" requires speculation on the TNPP lost as a result of human activities.

[3] Data in the literature usually are presented as (i) means ± standard deviations, (ii) ranges, or (iii) means. Where a choice was available, I selected the data format according to the above order. I consider global-scale studies to be those whose data are chosen to represent the country scale or larger. To reduce subjectivity, I filtered out data that would require significant manipulation (e.g., incorporating allometric rules) to be used by our model.

Table 1.1. Description of variables in the formula used with updated estimates[4,5,6].

Source variable	Description	Prior estimate (Vitousek et al. 1986))	Contemporary mean	SD / mean	Number of samples
A_{ag} (m^2)	Area of agricultural land	1.6×10^{13}	1.3×10^{13}	0.33	11
A_{fc} (m^2)	Area permanently cleared for population increase and colonization	1.2×10^{11}	1.3×10^{11}	0.23	7
A_{gcp} (m^2)	Area of forest converted to grazing for all time	7×10^{12}	3.3×10^{12}	0.50	1
A_{ho} (m^2)	Area of human-occupied lands	2×10^{12}	1.8×10^{12}	1.2	4
A_s (m^2)	Area of savannah	1.5×10^{13}	1.7×10^{13}	0.46	8
A_{sctrf} (m^2/year)	Area cleared in tropical virgin forests by shifting cultivation	1.0×10^{10}	3.8×10^{10}	0.79	3
A_{tp} (m^2)	Area of tree plantations	1.5×10^{12}	1.2×10^{12}	0.18	6
B_{fc} (Pg/m^2)	Biomass of forest areas permanently cleared for population increase and colonization	2.2×10^{13}	3.3×10^{13}	0.91	61
B_{scs} (Pg/m^2)	Biomass of savannah in shifting cultivation (including below-ground)	8.5×10^{12}	5.6×10^{12}	1.1	23
B_{sh} (Pg/m^2)	Biomass of above-ground grasses in burned savannah	3.9×10^{11}	6.7×10^{11}	0.60	14
B_{strf} (Pg/m^2)	Biomass of secondary tropical forest (including below-ground)	1.8×10^{13}	1.7×10^{13}	0.65	20
B_{trf} (Pg/m^2)	Biomass of tropical forests (including below-ground)	3.9×10^{13}	3.6×10^{13}	0.58	43
CR_{sc} (m^2 person^{-1} year^{-1})	Clearing rate of shifting cultivation	2.0×10^3	1.7×10^3	0.16	5
NPP_{fwd} (Pg/year)	NPP of firewood	1.0	0.90	0.80	10
NPP_{lse} (Pg/year)	NPP eaten by livestock	2.2	3.6	0.53	5
$P_{fb/mf}$	Proportion of forest biomass relative to merchantable fraction	2.1	2.7	1.2	21
$P_{fwd/lc}$	Proportion of firewood that is met by land clearing and cultivation	0.30	0.65	0.75	2
P_{gbnl}	Proportion of burning on natural grazing lands	0.43	0.43	0.50	1
P_{ho}	Proportion of productive human-occupied lands	0.40	0.40	0.50	1
$P_{lgnp/gp}$	Proportion of natural pasture grazed by livestock relative to all grazed pasture lands	0.50	0.50	0.50	1
$P_{lse/nl}$	Proportion of NPP eaten by livestock that comes from natural lands	0.68	0.87	0.50	1
P_{nhfwd}	Proportion of firewood harvested but not used every year	0.50	0.50	0.50	1
POP_{sc}	Population that uses shifting agriculture	2.0×10^8	4.5×10^8	0.15	2
PR_{ag} (Pg m^{-2} year^{-1})	Productivity of agricultural lands	9.4×10^{13}	9.0×10^{13}	0.55	16
PR_{gcp} (Pg m^{-2} year^{-1})	Productivity of lands converted to pasture	1.4×10^{12}	1.1×10^{12}	0.82	37
PR_{ho} (Pg m^{-2} year^{-1})	Productivity of human-occupied lands	5.0×10^{13}	3.5×10^{13}	0.60	2
PR_{tp} (Pg m^{-2} year^{-1})	Productivity of tree plantations	1.75×10^{12}	1.60×10^{12}	0.81	8
P_{sb}	Proportion of savannah burned annually	0.40	0.40	0.75	9
P_{scs}	Proportion of shifting cultivation in savannahs	0.43	0.46	0.41	5
P_{scstrf}	Proportion of shifting cultivation in secondary tropical forest	0.57	0.64	0.42	6
P_{tp}	Proportion of wood that humans use of tree plantation origin	0.25	0.22	0.50	1
ρ_w (Pg/m^3)	Density of fiber/construction wood	6.0×10^{-10}	5.6×10^{-10}	0.55	17
V_{fhct} (m^3/year)	Volume of temperate forest harvest for construction/fiber wood	1.65×10^9	1.1×10^9	0.1	52
V_{fhctr} (m^3/year)	Volume of tropical forest harvest for construction/fiber wood	4.0×10^8	3.9×10^8	0.50	1

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[4] Criteria for inclusion in database: a) for parameters expected to significantly change with time, sources must be published no later than 1990, b) sources must be primary, or a manipulation of secondary information, c) sources represent data at a global or meta-country scale; plot scale studies are not included.

[5] Weights are in units dry matter. For source values and references see Appendix F.

[6] I used the following conversions in compiling the literature: 5 kcal/g OM (organic matter), 0.16 root/shoot ratio for tropical forests. Where data needed to be divided by area, I used estimates of average area in Table 1.

Reflecting the format of Vitousek *et al.*(Vitousek et al. 1986) and the majority of data sources, I present biomass and productivity values in terms of the weight of dry matter (DM). Conversion of data from weight carbon (C) to DM included a 10% uncertainty in carbon content (0.45 to 0.50 g C per g DM), reflecting commonly cited carbon values (Whittaker and Likens 1973a, Atjay et al. 1979, Armentano and Ralston 1980, Brown and Lugo 1982, 1992, Winjum and Schroeder 1997).

I estimated uncertainty for parameters with only one or two literature references using either literature-cited values or an *ad hoc* estimate that the standard deviation was one-half of the mean[7,8]. Although 8 of 34 parameters are estimated with a single measurement, the median number of measurements per parameter is 5.5, indicating that half of the parameters have enough independent measurements to provide at least rudimentary evaluation of their uncertainty. Only nine parameters have normalized 2σ error bounds less than unity, indicating that most parameters are not well known. Uncertainty in the parameters, however, does not significantly increase and correlate with sample size ($r^2 = 0.10$ for estimates using three or more samples), which reflects the fact that the literature-based estimates I used are derived, either directly or indirectly, from physical measurements. Differences between my mean estimates and those of Vitousek *et al.* (Vitousek et al. 1986) represent updates using newer literature. Coincidentally, the median difference for all 34 of the parameters is negligible, -1.2%.

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[7] Four of the parameters (P_{gbnl}, P_{ho}, $P_{lgnp/gp}$, P_{nhfwd}; see Table 1 for definitions) are difficult to estimate because of the absence of data in the literature. I used the ad hoc estimates of (Vitousek et al. 1986).

[8] The ad hoc estimate of error I use, 0.50, is slightly less than the mean error for parameters with multiple data, 0.60.

In addition to using more contemporary and larger scale measurements, I explicitly incorporated uncertainty in the estimate of HTNPP through stochastic simulations. Monte Carlo techniques allow each parameter to vary randomly constrained by its mean and estimated variance. I derived an estimate of variability in our knowledge of HTNPP by repeating these calculations 1 million times[9].

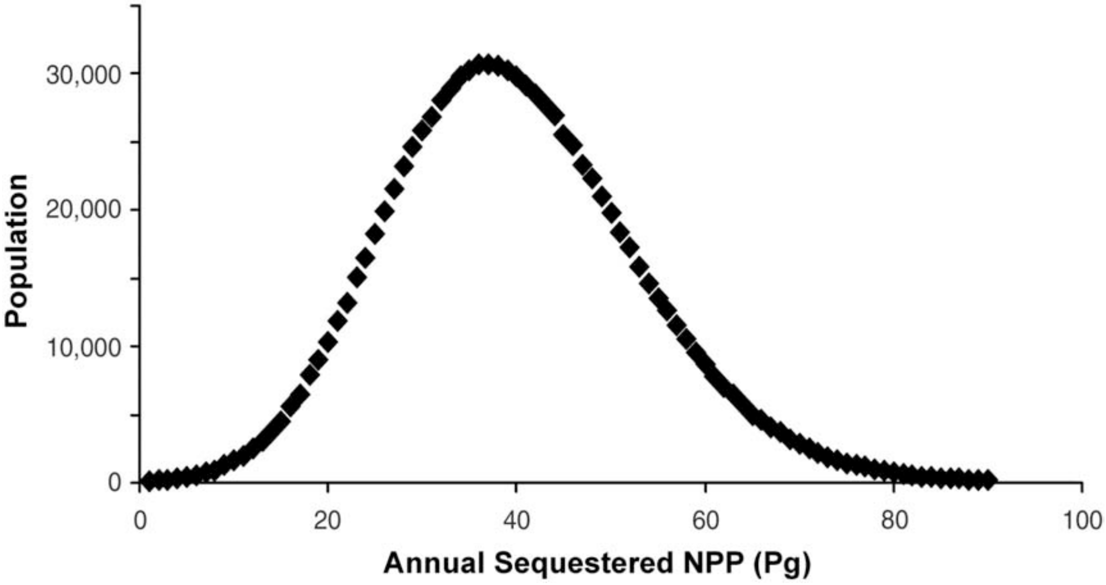

Figure. 1.2. Histogram of estimate of HTNPP allowing all parameters in the formula to vary with limits set by their estimated uncertainty. Histogram represents 1 million simulations. All independent parameters were constrained to be greater than zero. "Population" refers to the number of estimates represented by each data point on the plot.

Our mean estimate of HTNPP is 39 Pg DM (20 Pg C, where I assume carbon is 50% of dry matter) (Fig. 2) or 32% of TNPP[10], which almost precisely matches that of Vitousek *et al*. (Vitousek et al. 1986). This agreement is coincidental because the newer

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[9] It would be possible to derive some of the uncertainty in our estimate of HTNPP analytically, especially for aspects that involve simple summation of independent parameters. However, given that many of the parameters are multiplied and that I wished to constrain parameters to be non-negative, the Monte Carlo approach is necessary.

[10] I assumed that TNPP is 120 Pg, which is a mean value derived from 30 references since 1990. For these estimates and references, see *Appendix A-F*.

estimates of the parameters are considerably different from those of Vitousek *et al*. The mean absolute difference between my estimate of the contributing parameters and those of Vitousek *et al*. is, excluding the values for four parameters[3] directly assumed from (Vitousek et al. 1986), 37%; positive differences in some parameters are fortuitously canceled by negative differences in others.

Five parameters (Table 1.1), two of which are area calculations, have updated estimates with standard error bounds below or above the estimates of Vitousek *et al*. (Vitousek et al. 1986): area of forest converted to grazing (A_{gcp}), area of tree plantations (A_{tp}), clearing rate of shifting cultivation (CR_{sc}), population that uses shifting agriculture (POP_{sc}), and volume of forest harvest for wood used for construction and fiber in temperate areas (V_{fhct}). With the exception of CR_{sc}, each estimate is based on limited updated data and relies heavily on recent compilations from the Food and Agriculture Organization (FAO) of the United Nations (FAO 1990, 1992, Pandey 1995, FAO 1995a, Pandey 1997, Bull et al. 1998, Brown 1999). It is debatable whether updated estimates for these parameters are more valid than those obtained earlier, but in any case, these five parameters have little bearing on the results. The mean estimate of HTNPP is unchanged at 39 Pg if I use the earlier estimates (Vitousek et al. 1986) for these parameters. However, the variance in the estimates of parameters does influence uncertainty in the estimate of HTNPP significantly. The 95% confidence intervals in the estimates of

HTNPP are ±27 Pg DM (14 Pg C)[11]. These error bounds are so wide that mean estimates of HTNPP like that obtained here and earlier have limited utility.

Although there is a large degree of uncertainty, it is clear that human impact on TNPP is significant. The lower bound on the estimate (12 Pg DM, 6.0 Pg C), although nowhere near total TNPP, indicates that humans have a large impact on biological resources.

The uncertainty in the estimates also has implications for assessing the state of human use of fresh water. Postel *et al*. (Postel et al. 1996) used mean estimates of HTNPP obtained from Vitousek *et al*. (Vitousek et al. 1986) to estimate that 26% of all terrestrial ET is appropriated by humans. The high degree of uncertainty in our understanding of HTNPP means that Postel *et al*.'s estimate may significantly overestimate or underestimate human appropriation of ET. Given our relatively poor knowledge of HTNPP, at this point true extent of human impact on our plant and water resources is unclear.

I reran the Monte Carlo simulations and systematically held every variable constant except one to determine the influence of variability of each parameter on the estimate of HTNPP (Fig. 3). The most significant variables are agricultural productivity (PR_{ag}) and biomass of secondary tropical forest (B_{strf}). Estimates of PR_{ag} and B_{strf} are extensive in the literature, but they vary widely. It is not surprising that there would be a high degree of variability in these parameters. PR_{ag} and B_{strf} can be expected to be highly heterogeneous.

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[11] Our estimates of uncertainty are conservative in that (i) estimates of parameters are not independent (i.e., they are influenced by older literature, and some newer estimates are reworkings of older ones), and (ii) uncertainty due to assumptions in the model used (template, Fig. 1) is not included.

Depending on fertilizer, irrigation, and crop type, PR_{ag} can vary by as much as a factor of 5 from field to field[12] (Whittaker and Likens 1973a, Potter et al. 1993).

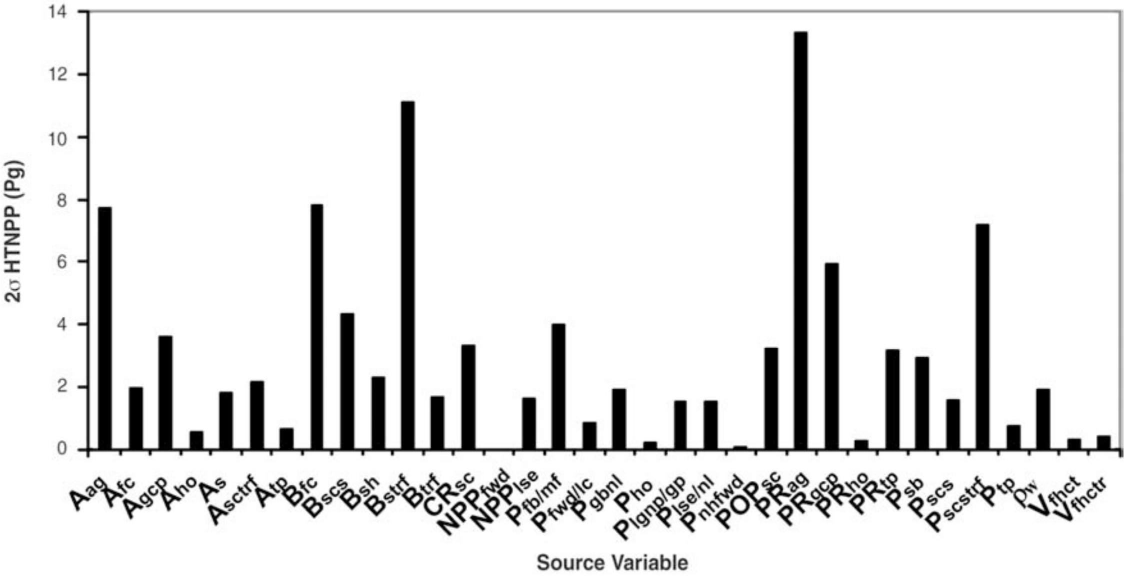

Figure . 1.3. Sensitivity analysis showing key independent parameters that strongly influence uncertainty in the estimate of HTNPP. Analysis was performed by systematically holding all variables (except one) constant and equal to their mean. Each parameter was allowed to vary randomly 1 million times.

Uncertainty in three other parameters - area of agricultural lands (A_{ag}), biomass of forest areas permanently cleared for population increase and colonization (B_{fc}), and proportion of shifting cultivation in secondary tropical forest (P_{scstrf}) - contributes significantly to the uncertainty in HTNPP (greater than 6 Pg DM variation). Two of these parameters are area calculations and indicate that our lack of knowledge extends to what should be relatively simple parameters to measure precisely.

Our analysis indicates that the assessment of human limits to plant and water use will require better estimation of some highly heterogeneous parameters, including global

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[12] A well-known study (Lieth 1973) used frequently by others has a typographical error (H. Lieth, personal communication) in its estimate of productivity of cultivated land, and I filtered out its estimates in our analysis.

productivity of agricultural, grazed, and human-occupied lands. Reduction in the uncertainty of these parameters will likely demand detailed worldwide assessment through a combination of many pieces of information, including satellite data, national crop figures, and patterns of irrigation and fertilizer use. Without these types of future assessments, the magnitude of the human footprint on Earth is open to much speculation.

Chapter 2. Quantification of land cover change impact on global evapotranspiration and net primary productivity

2.1 Introduction

In addition to atmospheric composition, astronomic factors, ocean currents, and tectonics, land cover change can impact global climate (Claussen 2004). The most direct way that land cover change impacts climate is through modification of its surface-to-atmosphere fluxes, ET and NPP, of the global water, and carbon cycle, respectively. Alterations of the land surface affect available energy and water, photosynthesis, nutrients, and surface roughness, and thus both the timing and magnitude of ET and NPP.

Recent advances of earth observations, both satellite- and land-based provide new data (Loveland et al. 1998, Baldocchi et al. 2001, Justice et al. 2002) for assessments of human impact on ET and related fluxes. Hydrologic studies during the past three decades have produced over 1000 field and model-based estimates of annual ET associated with single land cover types. These estimates form a valuable resource for understanding land cover, freshwater use and NPP, and provide an independent check on general circulation model estimates and satellite-based estimates of ET (Nishida et al. 2003). At present, validation options are limited for global annual ET estimates for discrete land covers.

Measures of how humanity impacts Earth are essential to manage our planet, giving the perspective of what stage humanity is at in its development, indicating the potential for future unlimited growth, and indicating the relative strength of the drivers for global change. Human impact on ET and NPP are key indicators for our impact on Earth as they show how humans alter the magnitude of land surface-atmosphere interactions at a global scale. Estimates of human "appropriation" of earth's resources are popular measures of this impact (Vitousek et al. 1986, Postel et al. 1996, Rojstaczer et al. 2001).

Appropriation has been first defined as a measure of the amount of the flux or mass, most commonly ET or NPP, touched (but not necessarily altered) by human activity (Vitousek et al. 1986, Postel et al. 1996, Rojstaczer et al. 2001, Imhoff et al. 2004). Others (Haberl et al. 2001, Krausmann et al. 2003) use appropriation defined as a change in flux from human land cover change. The most cited statistic of human impact on the global water cycle is that humans appropriate 26% of global total terrestrial ET (TET) (Postel et al. 1996), yet it is in error, because the conversion of appropriated NPP (HANPP) (Vitousek et al. 1986) to TET by the global scale relation that follows (HANPP*(TET/TNPP))/(TET), and the ET components cancel out of the equation.

In addition, there is confusion in the literature in interpretation of appropriation statistics. For example, appropriation measures (Postel et al. 1996) have been used incorrectly to make assessments of changes in the availability of fresh water (UN 2003b). Because of the ambiguity of "appropriation" here I instead use "occupation" to describe the amount of NPP and ET "space" we occupy, and use "change" to describe the increase or decrease in TET flux and annual NPP caused by land cover transformations. Surprisingly there is no other estimate of the impact of the present extent of anthropogenic land cover change on global annual ET. Studies with atmospheric general circulation models (Betts 2001, Zhao and Pitman 2001, Bounoua et al. 2002) have yet to provide statistics of human land cover change on the global annual fluxes; also, they examine the effect of one or two types of human-dominated land cover and, as a result, transform a smaller area of the land surface.

Here I gather census, ET, and earth observation data into a database and estimate the extent of land cover change to estimate the extent of occupied ET, and change in global annual ET and NPP from land cover change.

2.2 Methods

Database. I assemble estimates of transformed areas, and fluxes of NPP and ET, from published estimates in the literature into a database (Appendix A-F), to estimate the magnitude of occupation of land and TET, and change in TET resulting from land cover transformations. The database includes data collected with a wide variety of measurements over a wide range of scales from plot studies, catchments, country surveys, global scale modelling and remote sensing (Table 1.1). For variables with less than three estimates, I assign a standard deviation by applying a ratio of standard deviation to mean of 0.45. The average of this ratio for the other variables is 0.44. I also apply this procedure also to area of grazing land, A_{gz}, because the four estimates do not appear to be independent; the standard error is only 2%, conspicuously less than the standard error for other area variables, and there is no evidence that A_{gz} should have a considerably smaller uncertainty. Outliers, defined as estimates more than two standard deviations from the mean, are removed.

Area estimates are constrained to be recent (less than 13 years old). I do not include "indirect" anthropogenic cover changes such as desertification, water basin transfers, fire suppression, climate change, pollution induced changes, deforested lands that are abandoned, or lands impacted by war. The estimates of occupation and change are thus conservative. I consider tropical areas as those whose latitude is less than 30^{o} N or S. The estimate of TET, 6.4×10^{13} m^{3}, derived from summation of average ET from the database for IGBP biome areas, including human transformed land classes, is within the range of published estimates of TET, which vary from 62,000 to 75,000 km^{3}.

Uncertainty and sensitivity analysis. I use Monte Carlo analyses to estimate uncertainty in the parameter and its sensitivity to individual variables. I explicitly incorporate uncertainty in the estimates through one million simulations where each parameter is allowed to vary randomly, constrained by its mean and estimated variance. I examine the sensitivity of the estimate to individual by sequentially holding all variables but one constant and equal to their mean and rerun the analyses one million times. Variability in TET is not included in the uncertainty analysis.

HOTET calculations. I use the following equation to estimate human occupied TET with low ecological resolution:

$$HOTET_{GSR} = \frac{\sum_{hlc} (ET_{hlc} * A_{hlc})}{TET} \qquad (2.1)$$

where *GSR* denotes the global scale resolution of the estimate, *hlc* denotes the six human impacted land covers, and *A* represents area.

Next, I use direct estimates and bin the six land cover classes into smaller ecological units defined by temperate / tropical subdivisions or, for forested lands, the International Geosphere Biosphere Programme (IGBP). Global scale estimates are separated into more refined categories in an effort to reduce uncertainty.

$$HOTET_{HSR} = \frac{\sum_{hlc,HSR}(ET_{hlc,HSR} * A_{hlc,HSR})}{TET} \tag{2.2}$$

where *HSR* denotes the finer resolution of ecological categories.

I examine the impact of lumping smaller biomes into a single mean global ET for unimpacted forest (ET_f) and grasslands (ET_{gs}) (Table 2.1). The mean ET estimates are similar for lumped and distributed estimates, 0.85 mm yr^{-1} and 0.83 mm yr^{-1} for the lumped and multiple biome forest estimates, respectively, and 0.54 mm yr^{-1} and 0.60 mm yr^{-1} for the lumped and multiple biome grazing land estimates. I use the lumped estimates for the calculations. While average NPP fluxes characteristic of a particular land cover have been widely estimated, ET fluxes have not; the ET data are less reliable spatially.

An alternative means of estimating occupied TET is to modify an existing approach (Postel et al. 1996) by using NPP estimates in conjunction with water use efficiency estimates; this approach, however, produces an equation that yields extremely high uncertainty because values of NPP_{hlc} can approach zero in the Monte Carlo simulations:

$$HOTET_{NPP} = \frac{(HONPP * \sum_{hlc}(\frac{ET_{hlc}}{NPP_{hlc}} * P_{HONPPhlc}))}{TET} \tag{2.3}$$

HΔTET calculation. I estimate changes in annual TET by calculating the difference between human impacted land cover ET and that expected to be present without human activity. For this estimate I categorize potential land cover into forests, wetlands, grasslands, and barren lands

$$H\Delta TET = \frac{\sum_{hlc}\sum_{plc}((ET_{hlc} - ET_{plc}) * A_{hlc/plc})}{TET} \tag{2.4}$$

where $A_{hlc/plc}$ is the area of land converted to one of the six categories of anthropogenic land-cover multiplied by the proportion of area that lies with in a potential land cover type ($P_{hlc/plc}$), where *plc* is the potential land cover. Because of the lack of information on $P_{hlc/plc}$ in the literature a low number of potential vegetation categories is used.

HΔNPP calculation. Because *ET* and *NPP* are strongly linked (Choudhury 2000), estimates of changes in *TET* provide a surrogate measure of human induced changes in *TNPP* through the use of "water use efficiency" relations:

$$H\Delta TNPP_{TET} = \frac{\sum_{hlc}(H\Delta TET_{hlc} * \frac{NPP_{hlc}}{ET_{hlc}})}{TNPP} \tag{2.5}$$

where $H\Delta TNPP_{TET}$ is the change in NPP from land cover change, NPP_{hlc} is the mean NPP for the land cover, *TNPP* is the mean terrestrial NPP and NPP_{hlc}/ET_{hlc} are the water use efficiency relations for each land cover.

As expected, the empirically derived "water use efficiency" relations are higher in land covers with higher vegetation density: grazing, tree plantations and agriculture are the most efficient (2.2 and 1.9, 1.3 kg mET^{-1} yr^{-1} respectively), followed by biomass burned areas (0.76 kg mET^{-1} yr^{-1}) and areas with lowest human built-up areas (0.63 kg mET^{-1} yr^{-1}), and trailed by inundated lands (0.36 kg mET^{-1} yr^{-1})

2.3 Results and Conclusions

I include the following human-dominated land covers in the analysis: agriculture, tree plantations, human occupied areas, grazing land, land inundated by dams, and biomass burning, based on the criteria that they each cover at least 0.1 percent of the Earth's terrestrial surface and reflect direct use. Summing the human-dominated areas in the database I estimate humans occupy 41% of the terrestrial Earth. This estimate of occupied land is consistent with previous estimates. It falls within the 39-50% range previously estimated (Vitousek et al. 1997), and it is consistent with an estimate that wilderness covers 44% of the globe (Mittermeier et al. 2003), in that the remaining 6-17% of land may be accounted by fragmented land or land near roads that was not included in either occupied or wilderness classification. My estimate of land used for grazing and agriculture (35%) is similar to a previous estimate of 32% (Houghton 1994). The uncertainty in the global estimate of 41% is large, ±17% at a 95% confidence interval, reflecting the high degree of uncertainty in all area parameters except those related to tree plantations (a parameter whose low uncertainty likely reflects an absence of independent data sources). Land cover is dominated by grazing (Table 2.2), which takes place on roughly ¼ of the terrestrial Earth.

Table 2.1. Description of variables in the formulae [13]

Variable	Abbreviation	Mean	Standard deviation / mean	Number of estimates
Human Occupied Net Primary Productivity (g yr^{-1})	HANPP	3.9E+16	0.33	n/a
Human-occupied land				
Area of agricultural land (m^2)	A_{ag}	1.7E+13	0.37	16
Area of burned land (m^2)	A_b	1.75E+12	0.45	1
Area of built-up land (m^2)	A_{bu}	1.5E+12	1.2	7
Area of grazing land (m^2)	A_{gz}	3.4E+13	0.45	4
Area of inundated lands behind dams (m^2)	A_i	1.5E+12	0.45	1
Area of tree plantations and deforestation (m^2)	A_{tp}	1.2E+12	0.16	6
ET of agricultural lands (m yr^{-1})	ET_{ag}	0.72	0.53	62
ET of burned areas (m yr^{-1})	ET_b	0.66	0.70	3
ET of built-up lands (m yr^{-1})	ET_{bu}	0.56	0.40	28
ET of grazing lands (m yr^{-1})	ET_{gz}	0.50	0.49	42
Evaporation of inundated lands (m yr^{-1})	ET_i	1.1	0.44	61
ET of tree plantations (m yr^{-1})	ET_{tp}	0.86	0.52	54
ET of temperate agricultural area (m yr^{-1})	$ET_{ag\text{-}tm}$	0.63	0.48	48
ET of tropical agricultural area (m yr^{-1})	$ET_{ag\text{-}tr}$	1.0	0.38	11
ET of temperate burned areas (m yr^{-1})	$ET_{b\text{-}tm}$	0.5	0.45	1
ET of tropical burned areas (m yr^{-1})	$ET_{b\text{-}tr}$	0.7	0.45	2
ET of temperate built-up lands (m yr^{-1})	$ET_{bu\text{-}tm}$	0.55	0.35	24
ET of tropical built-up lands (m yr^{-1})	$ET_{bu\text{-}tr}$	0.62	0.50	5
ET of temperate grazing area (m yr^{-1})	$ET_{gz\text{-}tm}$	0.46	0.52	39
ET of tropical grazing area (m yr^{-1})	$ET_{gz\text{-}tr}$	1.1	0.23	5
ET of temperate inundated lands (m yr^{-1})	$ET_{i\text{-}tm}$	0.9	0.43	50
ET of tropical inundated lands (m yr^{-1})	$ET_{i\text{-}tr}$	1.9	0.25	12
ET of deciduous broadleaf tree plantations (m yr^{-1})	$ET_{tp\text{-}db}$	0.39	0.21	3

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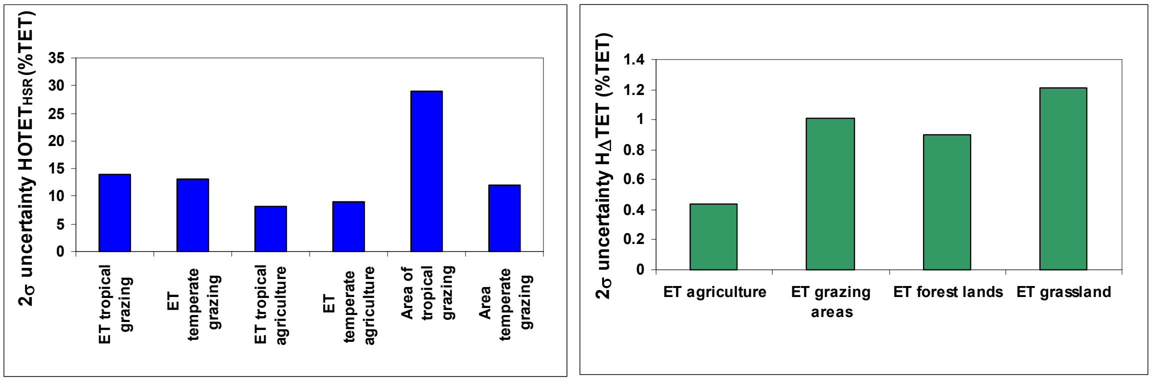
[13] For sources and source values, for proportions of land cover in each potential biome, and productivity variables, see supplementary data

ET of evergreen broadleaf tree plantations ($m\ yr^{-1}$)	ET_{tp-eb}	1.2	0.29	26
ET of evergreen needleleaf tree plantations ($m\ yr^{-1}$)	ET_{tp-en}	0.73	0.51	25
ET of mixed forest tree plantations ($m\ yr^{-1}$)	ET_{tp-m}	0.69	0.45	6
Lands not occupied by humans				
ET of forested areas ($m\ yr^{-1}$)	ET_f	0.84	0.53	275
ET of grassland, shrubland, savannah areas ($m\ yr^{-1}$)	ET_{gs}	0.54	0.60	136
ET of barren lands ($m\ yr^{-1}$)	ET_{barr}	0.18	0.42	30
ET of wetlands ($m\ yr^{-1}$)	ET_w	0.80	0.49	35

Of the two approaches to estimate the extent of human occupied TET (HOTET) (one with a lower ecologic unit resolution, $HOTET_{GSR}$, and one with a higher resolution $HOTET_{HSR}$), the less refined approach indicates that humans occupy 53% of annual TET ($3.4 \times 10^{13}\ m^3$). The higher resolution approach indicates that humans occupy 70% of annual TET ($4.5 \times 10^{13}\ m^3$). The two sigma uncertainty in these estimates is slightly lower for the second approach: 46% and 37% of annual TET (2.9×10^{13} and $2.4 \times 10^{13}\ m^3$) for the first and second method respectively.

Sensitivity analysis for $HOTET_{HSR}$ reveals that the ET fluxes associated with grazing and agriculture and areas of grazing land contribute the most uncertainty to the occupation estimate (Figure 2.1a), suggesting that further understanding of human occupation will especially benefit from better measures associated with grazing lands.

Figure 2.1. Sensitivity analysis showing key parameters that strongly influence uncertainty. a) occupied TET, higher resolution method (HOTET$_{HSR}$), and b) change in ET (HΔTET). I include parameters with a two sigma of 8% or greater.



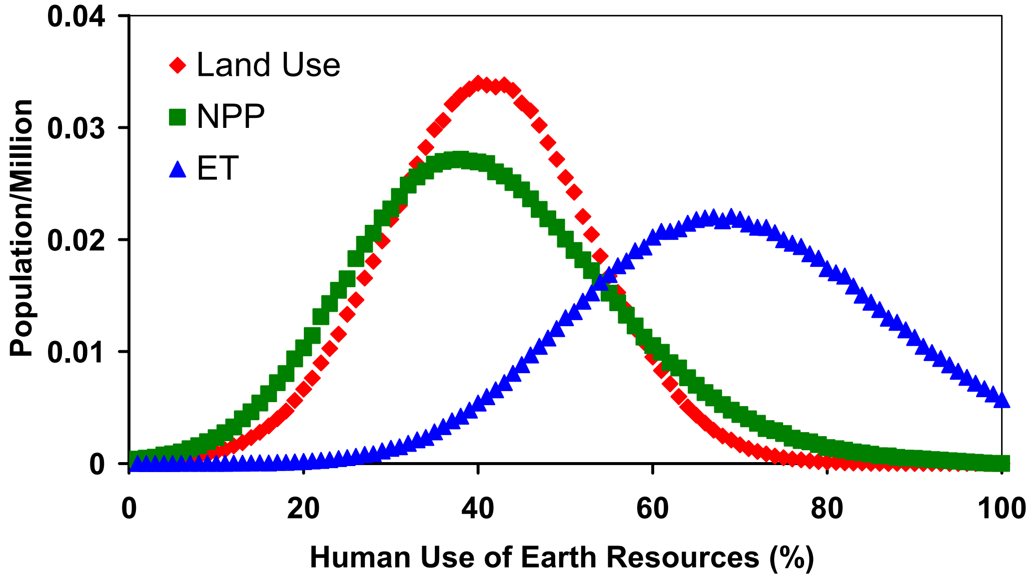
1a) 1b)

Table 2.2. Impact of land cover transformation on terrestrial fluxes

Anthropogenic land cover	% Occupied land	% Occupied terrestrial evapotranspiration		% Changed terrestrial evapotranspiration	% Changed net primary productivity
		GSR	HSR		
Grazing Lands	24%	27%	41%	-6.4%	1.0%
Agriculture	12%	19%	21%	1.6%	-7.5%
Burned Areas	1.3%	1.8%	1.8%	0.082%	0.033%
Inundated Lands	1.1%	2.6%	3.1%	1.0%	0.20%
Built-Up Lands	1.1%	1.3%	1.4%	-0.20%	-0.065%
Tree Plantations	0.86%	1.7%	1.6%	0.090%	0.087%
Total	**41%**	**53%**	**70%**	**-3.8%**	**-6.2%**

Comparison of HOTET with two other measures of human occupation, percent land cover and appropriated NPP (Figure 2.2), indicates that occupation of ET is much higher than the other two indices. Humans tend to occupy lands that have relatively high ET and relatively low NPP. Also, transformation of lands tends to decouple ET and NPP through such activities as reservoir creation and paving. Regardless, all three occupation measures indicate that humans have a pervasive impact on the surface of the Earth.

Figure 2.2. Human occupied land cover, terrestrial net primary productivity (NPP) and terrestrial ET ($HOTET_{HSR}$). Histogram of percent of total terrestrial from Monte Carlo analyses. I draw upon the database and a previous estimate (Chapter 1) to estimate occupation of land and net primary productivity (NPP).



To estimate change in ET, I compare ET in human-altered lands with ET in potential biomes. The mean estimate suggests that human activity has reduced global annual TET by 3.8% (2.4×10^{12} m^3) (Table 2.2). Grazing lands contribute the largest change, reducing annual TET by 6.4% (4.1×10^{12} m^3) (Figure 2.3a). Uncertainty in the estimate of HΔTET is high, with a 95% confidence interval of ± 55% of annual TET (3.5

x 10^{13} m^3) indicating that as with other global environmental parameters, better measurements and spatial resolution are necessary to estimate global impact with a high degree of confidence. In addition to the uncertainties regarding aerial estimation, there is debate on how conversion of grassland to grazing impacts NPP and therefore, ET (Painter and Belsky 1993, Frank et al. 1998); this is a large source of uncertainty because of the large areas that are impacted by grazing; a small change in estimated grazing area can create a significant estimated ET impact (Figure 2.1).

The global average statistic hides regional or activity-specific changes, because of increases in some aspects are cancelled out by decreases in others (Figure 2.3b). For example, areas where we reduce ET, such as clearing forest and wetlands for agriculture, are cancelled out on a global scale by areas where we increase ET. Thus while the global mean change in TET is relatively small, human activity can be expected to have larger impacts on the regional-scale hydrological cycle (Morrissey and Graham 1996, Ziegler et al. 2003). Individual components of change, tracking from one land cover type to another, can be substantial in a mean sense, approaching 4.7% (3.0 x 10^{12} m^3) (Figure 2.3b), and the absolute value of all changes to TET is considerable, 15% (9.5 x 10^{12} m^3).

Figure 2.3a. Mean contributions of individual anthropogenic land covers to change in global annual terrestrial ET and NPP.

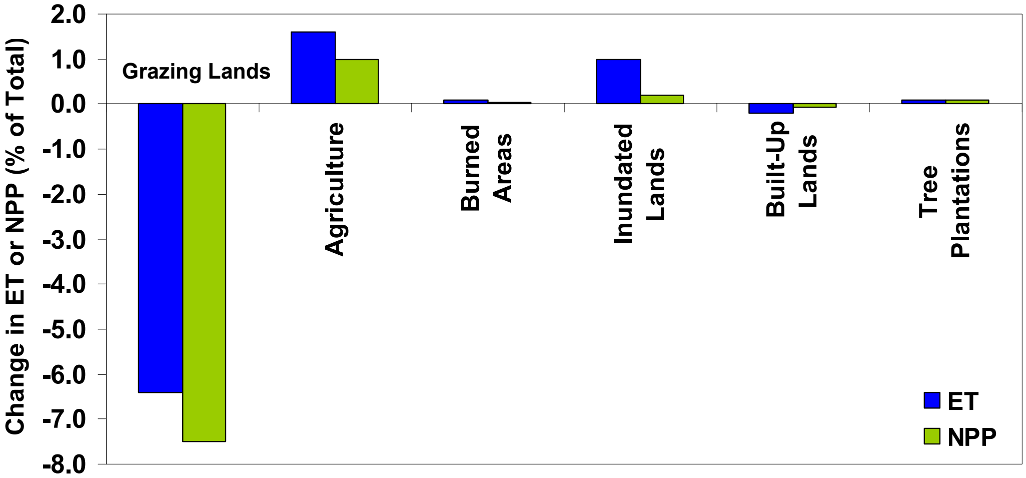
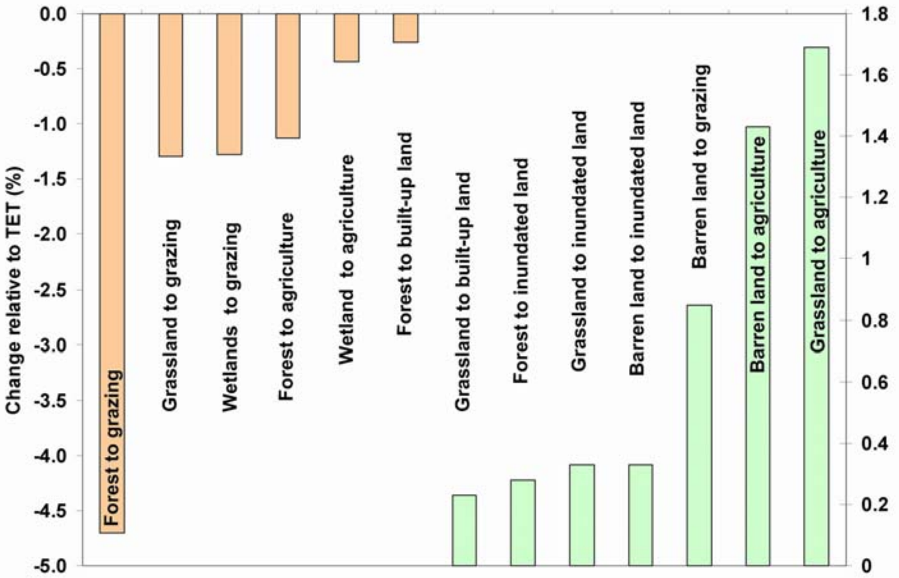


Figure 2.3b. Mean contribution of discrete land transformations to change in global annual terrestrial ET. Land transformations consist of a change from a discrete potential land cover to an anthropogenic land cover. I include variables that have an absolute value greater than 0.2%.



As noted above, the global estimate of changes in TET can be used to estimate changes in NPP (HΔTNPP) through the use of biome-scale water efficiency functions between TNPP and TET (equation 2.5). The resulting mean estimate suggests that humans have decreased terrestrial NPP by 6.2% (7.5 x 10^{15} g m^{-2} yr^{-1} or 3.4 x 10^{15} gC m^{-2} yr^{-1}), consistent with a previous estimate by that humans were reducing NPP by approximately 5% (DeFries et al. 1999). This similarity in the two estimates of changed NPP provides an independent corroboration for the estimate of changed ET (-3.8%).

Similar to the estimate of TET changes, regional effects can be substantial for NPP (Giambelluca 1986, Dow and DeWalle 2000), but globally the effects of negative components are cancelled out by positive components. These estimates of global change in TET and TNPP point to the need for better estimates of annual ET for different land covers, particularly in grazed lands. Further work should be done to improve estimation of the proportion of land cover change in each of the potential vegetation categories, and to improve estimates by examining variations over space (Niyogi et al. 2002).

Reductions to global ET and NPP can have implications for available water, and the annual amount of food produced on Earth. Because this system is highly nonlinear (Rial et al. 2004) large changes in climate and ecosystems may occur for small changes in, for example, ET. Reductions in ET can increase the amount of streamflow, and in some circumstances can reduce local precipitation (Bounoua et al. 2002).

The cumulative effects of land cover change are substantial relative to other human induced changes. The estimated change in HΔNPP is equivalent in mass to half that of the 2000 global, fossil-fuel CO_2 emission estimate (Marland et al. 2003) (1.2 x 10^{17} g DM/yr, or ~12% of TNPP), and the amount of change in ET from land cover change is equivalent to the volume of annual global water withdrawals (~3.5 x 10^{12} m^3 yr^{-1} or 4.9 % of TET) (Shiklomanov 2000a, Gleick 2003). Most notably, this estimate shows that the terrestrial hydrologic cycle may be altered more by the direct effects from land cover change than the indirect effect of anticipated greenhouse-gas induced climate change (estimated to increase by 2% as estimated for 2070-2100 as forced with projected changes in greenhouse gas concentrations and aerosol loading (Arora 2001)).

Given that half of TET is occupied by humans, the global temporal signature of ET is likely being altered by human activity; this is especially important since the increase or decrease in runoff depends on changes in the magnitude and timing of precipitation and ET (Arora 2001). For example, in temperate areas conversion of forests to urban areas can cause additional ET in the summer evening hours (Grimmond and Oke 1986), and conversion of forests to agriculture can result in less ET during the non-growing season.

Our occupation measures indicate that humans are now, more than ever before, the dominant megafauna on Earth, and the finite nature of land and fresh water resources implies that there are limits to human use. Occupation values are so large that without increased efficiency in use of land resources, humans will soon approach limits. To put occupation into context (Sanderson et al. 2002), I compare global economic and population growth to present occupation to estimate how long humans can sustain the present pattern of resource use. World annual population growth is currently 1.2% (UN

2003a), representing a doubling time of 58 years. Land use efficiency will have to be increased markedly, to avoid limits to land availability and NPP in the next 50 years.

Chapter 3. Distribution of Evapotranspiration Change from Global Anthropogenic Land Cover Change

3.1 Introduction

Reports in recent years claim that humanity is facing a global water crisis (Kirby 2004). Over the last 50 years in particular, the world's finite supply of freshwater has been subjected to increasing pressures and has also suffered quality degradation in many regions (UN 2003b). There is a possibility that humans could impact a global water crisis through land cover change.

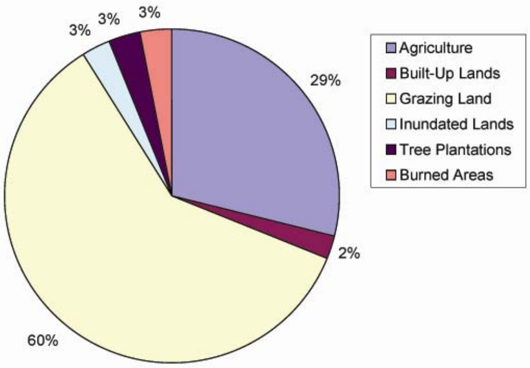


Figure 3.1. Relative areas of major anthropogenic land covers, as percentage of total transformed land (40%) (Table 2.1).

Humans have transformed approximately 40% of the Earth's land surface through activities such as urbanisation and agriculture (Figure 3.1). The land-atmosphere flux of the water cycle, evapotranspiration (ET), is closely related to land cover type, as it is driven by surface roughness, available moisture, available energy, and photosynthesis rates, all of which can be altered through land cover change (Bosch and Hewlett 1982, Bounoua et al. 2002). Alteration of ET can have wide-ranging effects: changing the amount of water available for runoff (as ET is increased, less water is available for rivers); changing the amount of rainfall by impacting the precipitation recycling rate (Bounoua et al. 2002); and finally, by changing the Bowen

Ratio, altering surface temperature; for example, if ET is reduced, more energy is available for surface heating or the sensible heat flux.

A long history of data from field experiments has demonstrated that land cover change can alter streamflow at the regional-scale, including hallmark studies such as at Wagon Wheel Gap in Colorado (Bates and Henry 1928) and Coweeta in North Carolina (Swank and Crossley 1988). More recently, modelling investigations have highlighted the effect that land use can have on ET. Regional-scale land surface modelling studies have demonstrated the impact of land cover change on the partitioning of available water between ET and runoff (Pitman 2003). For example, regional scale models have demonstrated the impact of land cover transformations on ET (e.g., conversion of prairie to farmland increased ET by 36%, (Mahmood and Hubbard 2002), and runoff (e.g., the Variable Infiltration Capacity hydrologic model showed that land cover change in the Columbia River basin resulted in increased streamflow of up to 10% (Matheussen et al. 2000)).

The ability to assess the impact of land cover change on climate at the global-scale has become possible with the advent of Atmospheric General Circulation Models (AGCMs) that incorporate land cover transformations by being coupled with Land Surface Models (LSMs). Modelling with AGCMs coupled with LSMs indicates that land cover change alters global climate, including temperature and precipitation (Kleidon et al. 2000, Betts 2001, Claussen et al. 2001, Bounoua et al. 2002, Maynard and Polcher 2002, Matthews et al. 2003); for example, such modelling has examined the sensitivity of global climate to tropical deforestation (Polcher and Laval 1994a, 1994b). AGCM modelling has also underscored the important role of soil moisture and ET in the global water cycle (Milly and Dunne 1994, Ducharne and Laval 2000).

No study has estimated the global-scale geographic patterns of change in ET from the suite of major current anthropogenic land cover changes. The modelling community has not yet directly examined how the current extent of land cover transformations acts to change annual ET, and previous to this study, accounting methods were not possible because of the lack of information on characteristic rates of ET for the suite of global biomes, as was done for NPP in the 1960s by (Lieth 1972). Modelling studies have commonly examined the effects of land cover change with emphasis on shorter-term fluxes of energy and climate effects, but not on annual scales of mass transfer required to examine the effect on the global water cycle. And, previous global scale modelling studies have examined the effect of one or two types of anthropogenic land use on climate and, as a result, take into account a reduced area of altered land cover. Moreover, modelling studies are limited in the number of land covers examined because the parameterisation of anthropogenic land covers has either not been developed or is very crude (Gervois et al. 2004). For example, for most global land-surface models that are coupled to AGCMs, there is no available parameterisation for urban lands, lakes, or wetlands.

How and where may human action be altering the water cycle? The goal of this study is to advance our understanding of how humans are currently impacting the land-atmosphere flux of global water cycle through land cover change, and to identify where land cover change may be most likely to alter runoff, driving increased flooding and water shortages. I examine how current anthropogenic land cover change is altering annual actual ET throughout the globe by using accounting methods made possible by the database of observed ET for individual land cover types (Appendix E), and by an assembly of maps of current distribution of anthropogenic vegetation and of potential global land cover, the land cover expected in the present-day climate had no human intervention occurred. The change is mapped at a high (~ 10 km) resolution.

3.2 Land Cover Mapping

I have assembled the global distribution of 17 separate land cover classes from various sources, comprising of 5 **h**uman/anthropogenic **l**and **c**overs (HLCs) and 12 **p**otential **l**and **c**overs (PLCs) (Table 3.1, Appendix G). The five HLCs (irrigated agriculture, non-irrigated agriculture, built-up areas, grazing lands and reservoirs created from dams) were chosen because: 1) they each cover more than 0.1% of the land surface, and 2) they represent a relatively permanent state of land cover change. Tree plantations, other deforestation not replaced by the 5 HLCs, and anthropogenically burned areas (such as fuelwood burning) were not considered for two reasons: 1) the land cover change in these cases is transient, and/or 2) a global map of these areas is not yet available.

The global maps selected are very recent, with irrigated agriculture, wetlands, reservoirs and grazing lands being produced in 2004. In cases where more than one available global map was available for a given land cover type, the map was chosen for our study based on the following criteria. The maps need to: 1) be up-to-date, produced no earlier than 1990, and incorporate recent advances, 2) have a vegetation classification that is compatible with the ET dataset, in that it has singular land cover classes that can be directly correlated to each of the PLCs and HLCs, and 3) have at least a 5 minute (~10 km) grid resolution, in order that the grids can define individual wetlands, urban areas, and impounded reservoirs. The global land cover maps are derived from a combination of sources, including satellite imagery and other remote sensing, ecological modelling, and country surveys (Appendix G). I enhanced the potential vegetation map to include wetlands because of the potentially important role of wetlands in the hydrologic cycle (Table 3.1, Figure G.5, Appendix G).

This study includes fifty-four types of land cover change, defined here as conversion from a PLC to a HLC (Table 3.1): five types of forest each converted to all five types of HLC; five types of grassland converted to irrigated and non-irrigated agriculture, urban and reservoirs, and also savannah conversion to grazing land; barren land converted into irrigated agriculture, urban and reservoirs, and wetlands converted into all five types of HLC.

ET change from grazing land and non-irrigated agricultural land is calculated when grazing land is converted from previously forested lands, savannah or wetlands[14]. Conversions of barren land, tundra, open shrubland and closed shrubland to grazing and non-irrigated agricultural land are not included because data of grazed and non-irrigated agriculture in such areas is not available. Further, ET change from grassland to grazing land is not included because grassland ET is used in part to calculate the grazing land ET.

A global synthesis of the five HLCs shows where land cover change is occurring across the globe (Figure 3.2). Agriculture and grazing alter huge expanses of the Earth;

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[14] ET change from conversion of grassland to non-irrigated agricultural land is included.

much of the original forest in southern former USSR, Europe and in south-east Asia, including China, India, and the grasslands of North America has been converted to agriculture (Appendix G). Central North America, Central Asia, Australia have the most extensive grazing (Figure G4). In contrast, reservoirs, irrigated areas, and urban areas alter more discrete areas (Appendix G). Urban development is most heavily concentrated in central Northern Europe, Japan, Korea and the Northeastern USA. Small reservoirs are scattered throughout the USA and southern Asia, while large reservoirs lie in Eastern Canada, Russia, and Finland and along rivers draining into the Atlantic Coast in Africa and South America. Irrigated agriculture occurs broadly in India, Pakistan, and China, and occurs intermittently in the Middle East, western and southern Europe, USA, and in parts of South America (Appendix G).

3.3 Database and Estimated Fields of ET

In spite of intense international interest in ET measurements (FAO/GTOS 2004), the suite of local estimates of annual actual ET previously has not been synthesized at the global scale. I have gathered over 1000 available annual actual ET observations that each define a single land cover type (Appendix E). Estimates of ET were gathered from journal and government publications and through personal communication with scientists, in particular those involved with international eddy covariance tower initiatives (for example FLUXNET (Baldocchi et al. 2001)). The database includes observations from sites distributed across the globe, covering the period 1822 to 2004, with records varying in length from 1 to 107 years. In the database of ET estimates, each ET estimate is characterized by a discrete land cover, using the classification of the 17 land cover classes (Table 3.1).

Table 3.1. Land cover classification scheme for ET database, and corresponding land cover map sources.

Land Cover Classification for This Study			**Land Cover Map Sources**		
Land Cover	**Class**	**Sub- Biomes**	**Reso-lution**	**Source**	**Source Map Classification**
Agriculture	anthropogenic	none	5 min	(Ramankutty and Foley 1998)	Percentage cover of agriculture
Irrigated Agriculture	anthropogenic	none	5 min	(Siebert et al. 2005)	Percentage cover or irrigated agriculture
Built-Up Lands	anthropogenic	none	5 min	(Miteva 2004)	Percentage cover of urban areas
Grazing Land	anthropogenic	none	5 min	(Ramankutty 2004)	Percentage cover of grazing land
Inundated Lands	anthropogenic	none	½ min	(Lehner and Doll 2004)	Presence / absence of cells containing reservoirs
Forests	potential	Evergreen-Needleleaf (EN)	5 min	(Ramankutty and Foley 1998)	Temperate needleleaf evergreen forest / woodland, boreal evergreen forest / woodland
	potential	Evergreen-Broadleaf (EB)	5 min	(Ramankutty and Foley 1998)	Tropical evergreen forest / woodland, temperate broadleaf evergreen forest / woodland
	potential	Deciduous-Needleleaf (DN)	n/a	n/a	Lumped in with evergreen-needleleaf because no ET estimates available
	potential	Deciduous-Broadleaf (DB)	5 min	(Ramankutty and Foley 1998)	Tropical and temperate deciduous forest / woodland
	potential	Mixed (M)	5 min	(Ramankutty and Foley 1998)	Mixed forest
Grasslands	potential	Open shrubland (OS)	5 min	(Ramankutty and Foley 1998)	Open shrub
	potential	Closed shrubland (CS)	5 min	(Ramankutty and Foley 1998)	Dense shrub
	potential	Grassland (GS)	5 min	(Ramankutty and Foley 1998)	Grassland, steppe
	potential	Tundra (TU)	5 min	(Ramankutty and Foley 1998)	Tundra
	potential	Savannah (SA)	5 min	(Ramankutty and Foley 1998)	Savannah
Barren Lands	potential	none	5 min	(Ramankutty and Foley 1998)	Desert, polar desert, rock, ice
Wetlands	potential	none	½ min	(Lehner and Doll 2004)	Presence of wetlands

The ET point estimates were first entered into a Geographic Information System (GIS) (Figure 3.2). The largest number of ET observations are in North America (45%), followed by Europe (16%), Asia (13%), and South America (10%). While broadleaf forest, evergreen needleleaf forest and inundated land have the most ET estimates, barren-land has the highest spatial density of ET observations, followed by inundated lands, and forests (87, 75, and 70 observations per 10^6 km^2, respectively). Agriculture, grazing land and grassland have the lowest density of observations (6.2, 2.2, 2.6 observations per 10^6 km^2, respectively).

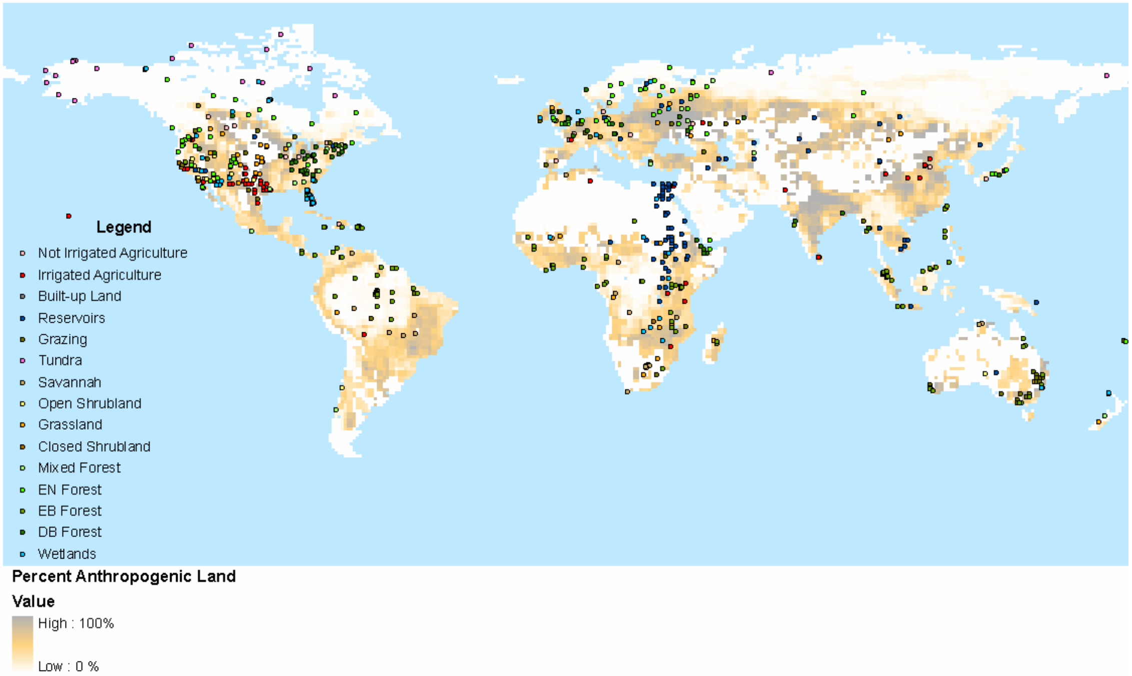


Figure 3.2. Distribution of estimates of actual annual ET for discrete land covers, and the extent of anthropogenically altered land surface, including from agriculture, grazing, reservoirs and urban land, at a 5 minute resolution. Details of mapping methods are in Appendix G.

There are areas of the globe where ET estimates are sparse (Figure 3.2), including India, central Asia, Argentina, eastern Russia and China. Considering individual land cover types, there are no estimates for deciduous broadleaf forest in the southern hemisphere; there are no ET annual estimates for deciduous needleleaf forest; there are no available ET estimates for the closed shrublands of Mediterranean Europe, and only one for sub-Saharan Africa; there are no estimates of ET for grassland biome, or its sub-biomes in Mexico; finally, there are few estimates of ET for the open shrublands of central Asia, Saharan and South-Africa, and Australia.

The point ET data were spatially interpolated using kriging to obtain a global field of ET for each land cover type. Detailed kriging methods are presented in Appendix H. Briefly, ordinary kriging was used, and the model (exponential, or spherical) and autocorrelation length were chosen based upon the variogram of ET data and the need for smoothing. A separate kriging approach was used for each of the 17 land covers.

The kriged fields were checked that they followed global trends in available water and energy by comparison with global climate maps, including precipitation (New et al. 1999), soil moisture (Willmott and Matsuura 2001), potential evapotranspiration, topography (Row et al. 2005), relative humidity (New et al. 1999), and an estimate of global annual ET, not divided into land cover type (Willmott and Matsuura 2001) (Figure 3.3b). In cases where the kriged field does not capture global trends in areas, estimates of annual actual ET were added, based upon other ET point-estimates from the database from similar land covers in similar climatic (Trewartha 1943), continental, land cover, topographic and latitudinal environments. For example, ET for open shrubland in the Middle East (dry climate, with precipitation in a cool winter, Bsk climate in the Koppen classification (Trewartha 1943)) was estimated from open shrubland data from central USA (also Bsk climate). The global annual ET spatial trends estimated by Willmott and Matsuura (2001) for 1950 - 1999, from observed precipitation and temperature measurements and a water budget model based on a modified Thornthwaite procedure, and ET variation with land cover type is not included in their estimate.

As a check on the estimates of global ET fields of potential vegetation I compared the sum of potential vegetation annual actual ET, 66,000 km^3/ year (adjusted to include missing land areas and lakes) to estimates of total terrestrial ET (Table E.11, Appendix E). This estimate of total terrestrial ET appears in the range published values (63,000 to 73,000 km^3/yr).

For each land cover type (Table 3.1) a mean and standard calculation were calculated from the observation means (Table 3.2). Evergreen broadleaf forest has the highest rate of ET, and built-up land has the lowest ET for HLCs and barren land has the lowest rate of ET for all land cover types. Inundated lands (reservoirs) and irrigated agriculture have the highest annual average ET of all the HLCs. Evergreen broadleaf forests, savannahs and wetlands have the highest annual average ET of the PLCs.

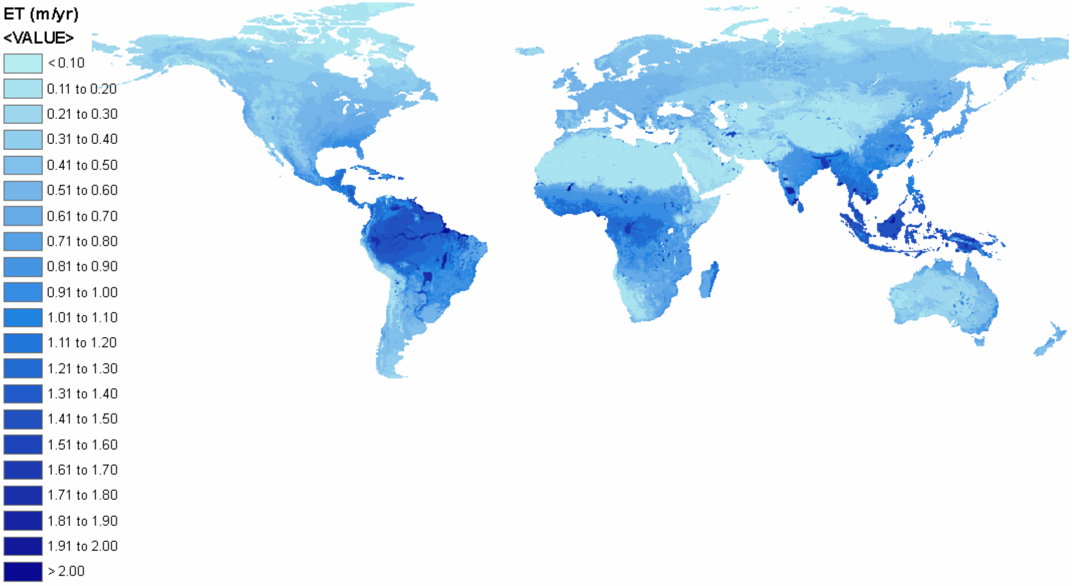
Table 3.2. Annual actual ET estimates for discrete land covers derived from kriging of point estimates. ET mean and standard deviation[15] (SD) is for all 5 minute cells in which the land cover type appears.

Land Cover	# of Obs.	Kriged Global ET Mean (m/yr)	Kriged Global ET SD (m/yr)
Non-Irrigated Agriculture	35	0.49	0.14
Irrigated Agriculture	70	1.0	0.41
Built-Up Lands	30	0.54	0.15
Grazing Land	74	0.65	0.21
Reservoirs / Inundated Lands	113	0.99	0.73
Deciduous Broadleaf Forests	76	0.77	0.11
Evergreen Broadleaf Forests	165	1.2	0.33
Evergreen Needleleaf Forests	110	0.50	0.19
Deciduous Needleleaf Forests	0	n/a	n/a
Mixed Forests	45	0.44	0.15
Grasslands	58	0.45	0.28
Savannah	18	0.74	0.21
Open Shrubland	37	0.34	0.18
Closed Shrubland	11	0.59	0.07
Tundra	24	0.19	0.04
Barren Lands	44	0.17	0.12
Wetlands	51	0.94	0.51
TOTAL	**1026**		

---

[15] standard deviation here refers to the positive square root of the kriged estimate variance in each grid cell, averaged for all cells

A. This study. ET for Potential Vegetation.



B. Wilmott & Matsuura, 2001. Present-day ET.

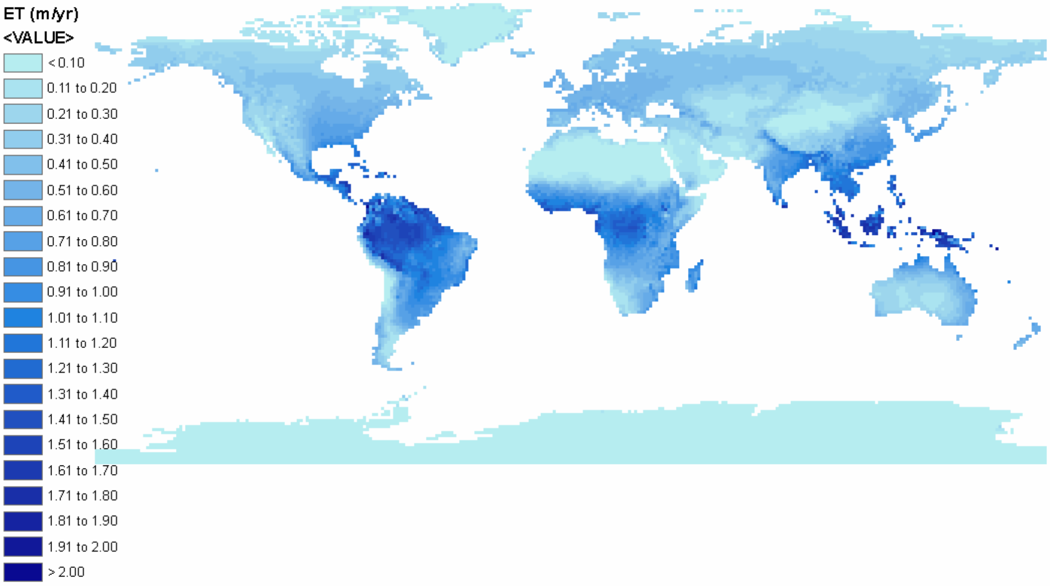


Figure 3.3. Gridded annual ET estimates, m/yr; a) potential vegetation for this study, total terrestrial ET = 66,000 km^3/yr, 5 minute resolution; b) gridded global ET estimates from Willmott and Matsuura (2001), total terrestrial ET = 57,000 km^3/yr, 30 minute resolution.

3.4 Change in ET with Land Cover Change (m/yr)

To examine how different land cover changes, for example change from mixed forest to agriculture, or from open shrubland to irrigated agriculture, alter annual ET, I calculated the difference in mean annual actual ET (m/yr) for each PLC / HLC (Table 3.1) in each 5 minute raster cell where an HLC occurs:

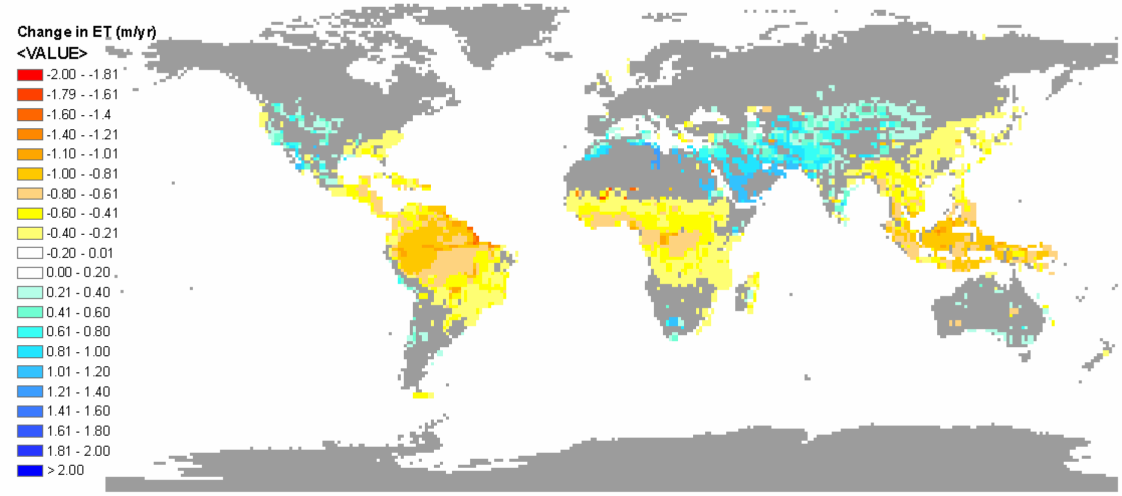
$$\Delta ET_{HLC-PLC} = ET_{HLC} - ET_{PLC} \tag{3.1}$$

The distribution of change in global ET shows some clear patterns for individual land cover changes. For conversion of PLC to agriculture, non-irrigated agriculture shows a decrease in ET, most marked over forest and wetland areas in the tropics (Figure 3.4a), and in conversion of wetland areas in the northern latitudes, for example, in central Northern Russia. In contrast, irrigated agriculture shows consistent increases in ET, most starkly in areas of the west-central USA, Africa, Middle East and Central Asia where irrigated agriculture replaces shrublands and desert areas. In general, there are not large changes in ET where temperate forests are converted to non-irrigated agriculture.

Conversion of potential vegetation to built-up land can both increase and decrease ET (Figure 3.4b). In general, where arid areas are converted to urban areas, there is an increase in ET, and areas of forest conversion to urban areas tend to decrease ET. An increase in ET is noted where drier areas have been converted to urban areas in central USA, Saharan Africa, Middle East and Central Asia. A decrease in ET from conversion of forests to urban areas is shown in tropical zones. The pattern of reduced ET, however, is not uniform for conversion of temperate forests to built-up land. While the urban areas converted from deciduous broadleaf forest in Germany show a marked decrease in ET, in the East-Coast of North America, urban areas converted from forest do not show a parallel decrease in ET. This may be explained by the differing nature of urban areas in the USA from Europe. In Europe urban areas tend to have higher density (Streich et al. 2004), while lawns, trees and pools are more common in the USA urban areas. While urbanisation can reduce ET through lowering available water for evaporation in urban areas, a recent study has shown that the additional heat from the urban canopy can advance the date of green-up and delay senescence in deciduous broadleaf forests in the Eastern USA (Zhang et al. 2004), lengthening the amount of time in the year in which trees transpire, and perhaps locally increasing ET. I do not include such changes in temporal cycles of ET in my analysis, however.

An increase in ET is associated with conversion of potential vegetation to inundated lands (Figure 3.4c). As expected, the increase is strongest where dry tropical areas are converted to reservoirs. A general decrease in ET is observed where grazing land replaces forest and savannah, and the decrease is most marked in former tropical forests and wetland areas (Figure 3.4d).

A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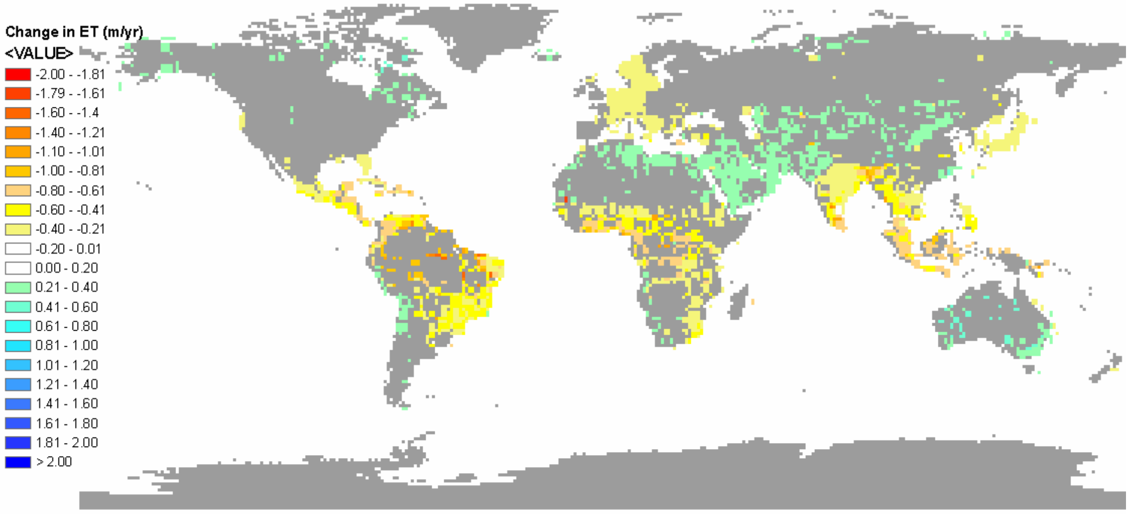
-1.60 - -1.4
-1.40 - -1.21
-1.10 - -1.01
-1.00 - -0.81
-0.80 - -0.61
-0.60 - -0.41
-0.40 - -0.21
-0.20 - 0.01
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.20
1.21 - 1.40
1.41 - 1.60
1.61 - 1.80
1.81 - 2.00
> 2.00

B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-1.60 - -1.4
-1.40 - -1.21
-1.10 - -1.01
-1.00 - -0.81
-0.80 - -0.61
-0.60 - -0.41
-0.40 - -0.21
-0.20 - 0.01
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00
1.01 - 1.20
1.21 - 1.40
1.41 - 1.60
1.61 - 1.80
1.81 - 2.00
> 2.00

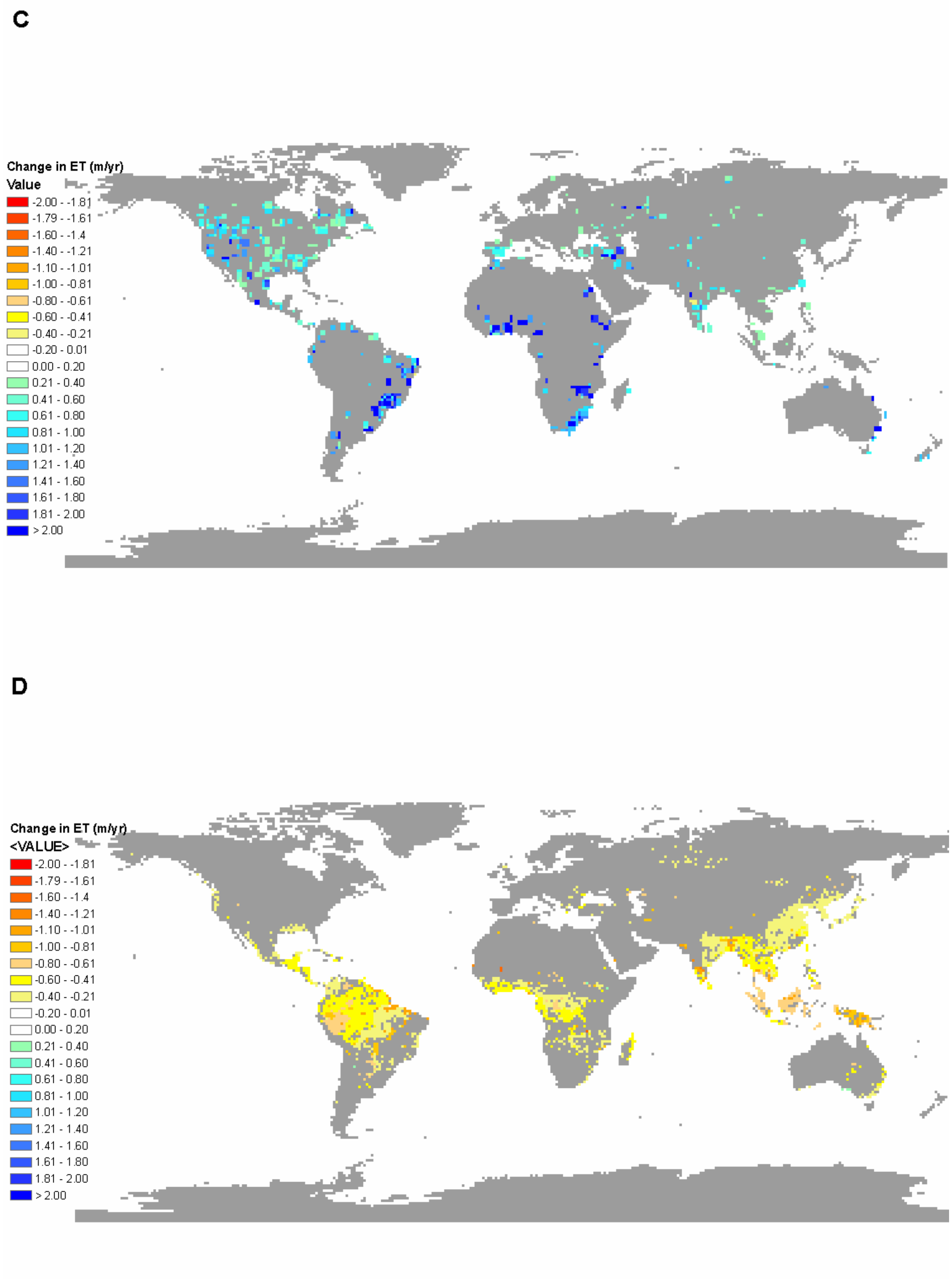

Figure 3.4. Change in ET from Potential Vegetation to HLC (m/yr). Change calculated at 5 minute resolution, and aggregated to 30 minutes for visualisation. a) change to agriculture, both irrigated and non-irrigated. b) change to built-up areas, c) change to reservoirs, d) change to grazing land.

As a global average, for all the land cover changes, the largest increase in ET occurs where barren land is converted to irrigated agriculture or reservoirs (Table 3.3). The largest reduction in ET occurs where wetlands are drained for non-irrigated agriculture, grazing land, and built-up land (Table 3.3). As a percent of the PLC ET, the data indicate that conversion of wetlands into non-irrigated agriculture causes the largest decrease in ET.

Table 3.3. Global average change in ET from potential vegetation classes to anthropogenic land covers. Changes of from potential sub-biomes are averaged for each biome class (Table 3.1). Percents are the HLC mean ET as a proportion of the PLC mean ET.

	Non-Irrigated Agriculture		Irrigated Agriculture		Built-up Land		Reservoirs		Grazing Land	
	m/yr	%	m/yr	%	m/yr	%	m/yr	%	m/yr	%
Forests	-0.26	-36	0.029	4.0	-0.13	-18	0.53	72	-0.23	-32
Grassland	-0.14	-30	0.045	10	-0.064	-14	0.80	174	-0.050	-7.0
Wetlands	-1.0	-106	-0.051	-5.0	-0.81	-86	-0.020	-2.0	-0.83	-88
Barren land	n/a	n/a	0.35	200	0.31	180	1.6	950	n/a	n/a

Comparison of our estimates of changed ET are coherent with estimates of changed ET from individual land cover change (Table 3.4) Where forest land is converted to shorter, un-irrigated vegetation such as grazing land, ET is reduced on average by 0.23 m/yr, consistent with previous studies (-0.018 to -0.5 m/yr) (Table 3.3). (Hoffmann and Jackson 2000) found that conversion of savannah to grassland reduced mean annual ET by 8-10% in tropical regions; our results show a similar decrease in ET from conversion of savannah to grazing land (-7%).

Table 3.4. Estimates of changes in local ET from land cover change from the literature. Abbreviations are for forest sub-biomes and are as follows: en = evergreen needleleaf, eb = evergreen broadleaf; m = mixed, db = deciduous broadleaf

Citation	*PLC*	*HLC*	*ΔET (m/yr)*	*Location*
Dugas et al., 1998	EN forest	grazing land	-0.018	Texas
Dunn & MacKay, 1995	EN forest	grazing land	-0.428	England
Jipp et al., 1998	EB forest	grazing land	-0.033	Amazon
Running et al., 1989	EN forest	grazing land	-0.05	Montana
Sun et al., 1998	forest	grassland	-10%	Florida
Hodnett et al., 1996	EB forest	grazing land	-0.438	Amazon
Weltz & Blackburn, 1995	EN forest	grazing land	0.081	Texas
Clarke & McCulloch, 1979	M forest	grazing land	-0.28	Wales
Dickinson & Kennedy, 1992	EB forest	grazing land	-0.26	Amazon
Lean & Rowntree, 1997	EB forest	grazing land	-0.157	Amazon
Manzi & Planton, 1996	EB forest	grazing land	-0.113	Amazon
Nobre et al., 1991	EB forest	grazing land	-0.5	Amazon
Calder, 2003	DB forest	grazing land	-0.093	England
Tattari & Ikonen, 1997	forest	grassland	-0.11	Finland

What physical processes explain the observed spatial patterns (Figure 3.4)? I summarise in Table 3.5 causes of change in ET from individual land cover changes identified in the literature. Land surface change can alter several or all of the dominant parameters that govern rates of ET, either those essential for ET to occur (available water and available energy), or those that enhance ET (LAI, an index of interception and transpiration potential, and surface roughness, an index of turbulent diffusion that maintains the vapour pressure gradient).

Table 3.5. Mechanisms driving altered ET from land cover change. A blue upward arrow signifies increased ET, and a red downward arrow signifies reduced ET from potential (horizontal) to anthropogenic land cover (vertical). The mechanisms are 1) H_2O, available water; 2) E, available energy, 3) Z_0, surface roughness[16]; and 4) LAI, the potential for interception and transpiration. The colour of the boxes filled indicates the observed direction of change in ET from Table 3.3, blue indicating increased ET, red indicating decreased ET. "ns" indicates that the change is not evident. "n/a" indicates the land cover change was not considered.

	Non-Irrigated Agriculture				Irrigated Agriculture				Built-up Land				Reservoirs				Grazing Land			
	H_2O	E	Z_0	LAI	H_2O	E	Z_0	LAI	H_2O	E	Z_0	LAI	H_2O	E	Z_0	LAI	H_2O	E	Z_0	LAI
Forest	↓ [17]	↓ [18]	↓ [15]	↓	↑	↓	↓ [15]	↓	↑ or ↓ [19]	↑ or ↓ [20]	↑ or ↓	↑ or ↓ [21]	↑ [22]	ns	↓ [23]	↓ [24]	↓ [16]	↓ [17]	↓ [15]	↓
Grass-land	ns	ns	ns	↓ [25]	↑ [26]	ns	ns	↓ [23]	↑ or ↓ [18]	↑ [27]	↑ [15]	↑ or ↓ [28]	↑ [21]	↑ [29]	↓ [30]	↓ [23]	↓ [31]	↓ [32]	↓ [33]	↓ [34]
Wet-land	↓	↓ [35]	ns	ns	ns	↓	ns	↓	↓	↑ or ↓	↑	↓	ns	ns	↓	↓	↓	↓	ns	↓
Barren land	n/a	n/a	n/a	n/a	↑	↑ [36]	ns	↑	↑ [37]	↑ [38]	↑	↑	↑	↑	ns	ns	n/a	n/a	n/a	n/a

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[16] surface roughness comparisons from (Sellers et al. 1996a) and (Sellers et al. 1996b).

[17] forests have increased access to soil water through deeper root structure

[18] forests have a lower albedo and trap more advected energy

[19] some urban areas may have pools and irrigated areas, making more available water, while others have reduced available water because of the numerous impervious surfaces and sub-surface drainage

[20] urban albedo is higher than forest, leading to reduced energy, however, heat added to the urban canopy from combustion and from increased heat storage in urban materials may lead to increased energy (Jin and Shepherd 2004)

[21] LAI is normally reduced, except for urban areas replacing barren environments (Zhang et al. 2004)

[22] there is more water available in reservoirs than in a forest or grassland

[23] the roughness length is smaller for a lake

[24] LAI is zero for a lake

[25] LAI is lower for cropland than for grassland because of the presence of bare soil in non-irrigated agriculture

[26] more water available in irrigated agriculture

[27] urban areas have increased available energy based on urban canopy effect (Arnfield 2003)

[28] LAI generally is lower for urban areas, except in areas where the LAI season is extended (Zhang, 2004)

[29] increased available energy from lower albedo in reservoirs from grasslands

[30] savannah has larger surface roughness than lakes

[31] increased access to soil water through deeper root structure; savannahs have greater rooting depth than do grasslands (Jackson et al. 1997); note, this change only includes *savannah* converted to grassland

[32] savannahs have lower albedo than do grasslands (Oguntoyinbo 1970)

[33] savannahs have higher surface roughness than do grasslands (Miranda et al. 1997)

[34] LAI lower for grassland than for savannah

[35] reduced energy from increased albedo

[36] assuming that the albedo would be reduced in irrigated agriculture

[37] from urban irrigation

In general, for each major type land cover change, there is a strong relation between direction of change of mechanisms that drive ET and the direction of observed change in annual ET (Table 3.5). Inferred change in available water correlates with the direction of observed change in every case; thus when there are differences in direction of change of the parameters, the direction of change in available water governs the direction of change to ET. Inferred change in available energy correlates with the direction of observed changes in ET, except for conversion of forest to irrigated agriculture. The largest percent response in ET to land cover change (Table 3.3) occurs where there are similar direction of change in all of the mechanisms. Grazing land, irrigated agriculture, non-irrigated agriculture and reservoirs tend to alter the ET in the same direction (either increase or decrease) for all potential vegetation covers, while built-up land can increase or decrease ET, as built-up land can either increase or decrease available energy, water, surface roughness and LAI (Table 3.5).

3.5 Change in ET volume

Here I create a global map of change in ET volume, from anthropogenic land cover change (Figure 3.4), by taking into consideration the area of each anthropogenic land cover each grid cell to calculate the volume change, and summing the changes of each HLC:

$$\sum_{HLC} \Delta ET_{HLC-PLC} * A_c * P_{HLC} \tag{3.2}$$

---

[38] heat added to the urban canopy from combustion and from increased heat storage in urban materials may lead to increased energy (Jin and Shepherd 2004)

where ΔET is the change in ET (m/yr), as calculated in equation 3.1, A_c is the area of the grid cell (m^2), P_{HLC} is the proportion of area covered by the HLC in the grid cell.

First, global average summaries of the change in ET are examined (Table 3.6). By summing each grid cell I calculate the total change in ET, HΔTET to be -4.1%, remarkably similar to that found in Chapter 2 (3.8%), even though different methods and different land cover changes are considered. By volume, agriculture is the anthropogenic land cover that alters the water cycle the most (Table 3.6), yet it is important to note that the potential for grazing land to impact ET has been constrained by censoring grassland to grazing land cover change.

Table 3.6. Change in ET m^3/yr from anthropogenic land cover change

	$\Delta ET_{HLC\text{-}PLC}$ (km^3/yr)	ΔET, as percent of Potential Vegetation (66 000 km^3)
Reservoirs	82	0.12 %
Grazing	-1100	-1.7 %
Built-Up	-40	-0.060 %
Agriculture	-1700	-2.6 %
TOTAL (HΔTET)	-2800	-4.1 %

This estimate of changed ET has a 95% confidence interval of +/- 36% of annual TET. I estimated the uncertainty of the estimate of changed ET by running Monte Carlo simulations on equation 3.2, allowing each parameter to vary randomly constrained by its mean and estimated standard deviation[39] (Table 3.2), repeating these calculations one million times.

While the global mean is uncertain, global patterns of reductions and increases in ET area more resilient. An advantage of representing the data in the map manner is that it allows for a check of ET change in particular areas, adding robustness to the estimate, by allowing the checking of local examples of ET and changed ET for particular land cover changes.

With the incorporation of all HLCs and their percentage areas, the results show the current extent of global anthropogenic land cover change creates broad areas of reduced in ET volume, interspersed with smaller areas where ET volume increases (Figure 3.5a), reflecting the more discrete geographic distribution of the HLCs tending to increase ET (irrigated agriculture, reservoirs) and the more extensive HLCs tending to decrease ET (non-irrigated agriculture, grazing) (Table 3.5, Appendix G).

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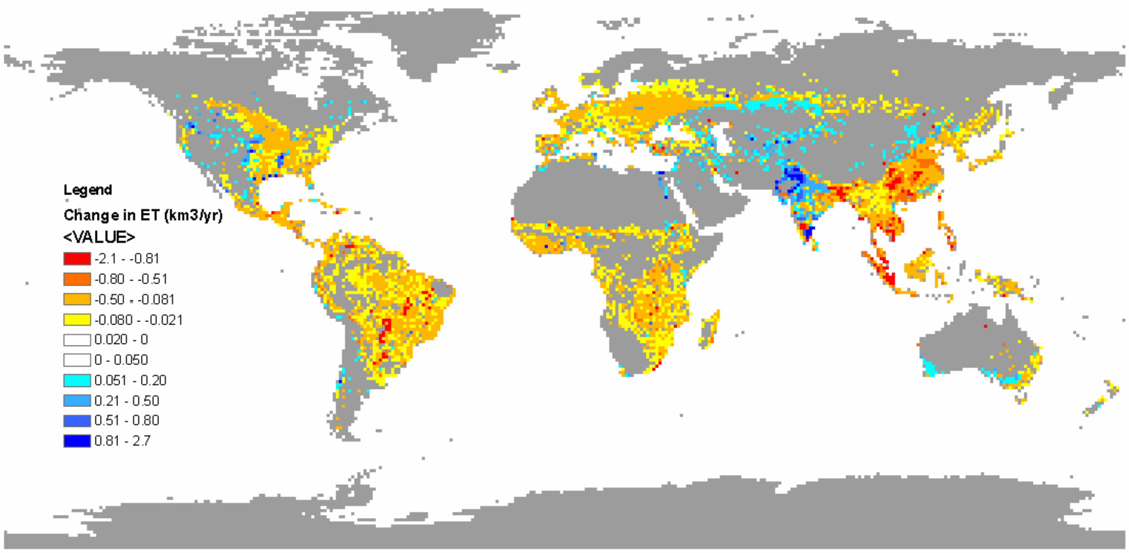
[39] The standard deviation of the area for each HLC is calculated from the ratio of standard deviation to the mean from Table 2.1.

A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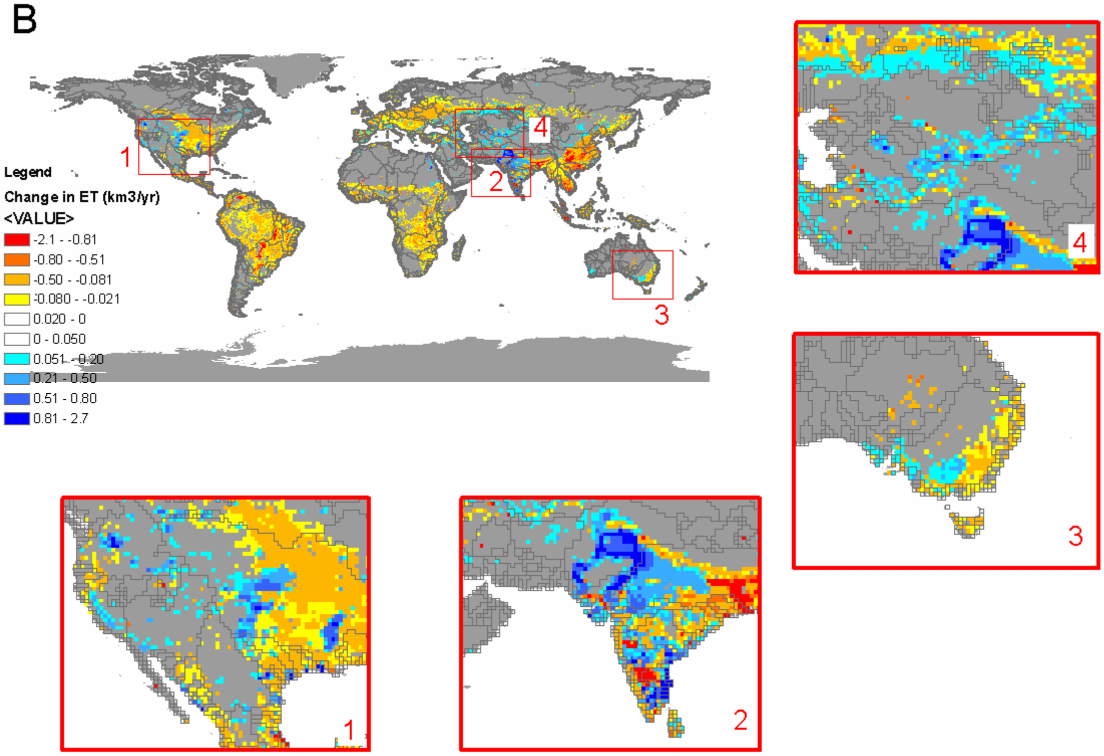
-0.50 - -0.081
-0.080 - -0.021
0.020 - 0
0 - 0.050
0.051 - 0.20
0.21 - 0.50
0.51 - 0.80
0.81 - 2.7

B


Legend
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-0.080 - -0.021
0.020 - 0
0 - 0.050
0.051 - 0.20
0.21 - 0.50
0.51 - 0.80
0.81 - 2.7
1
2
3
4

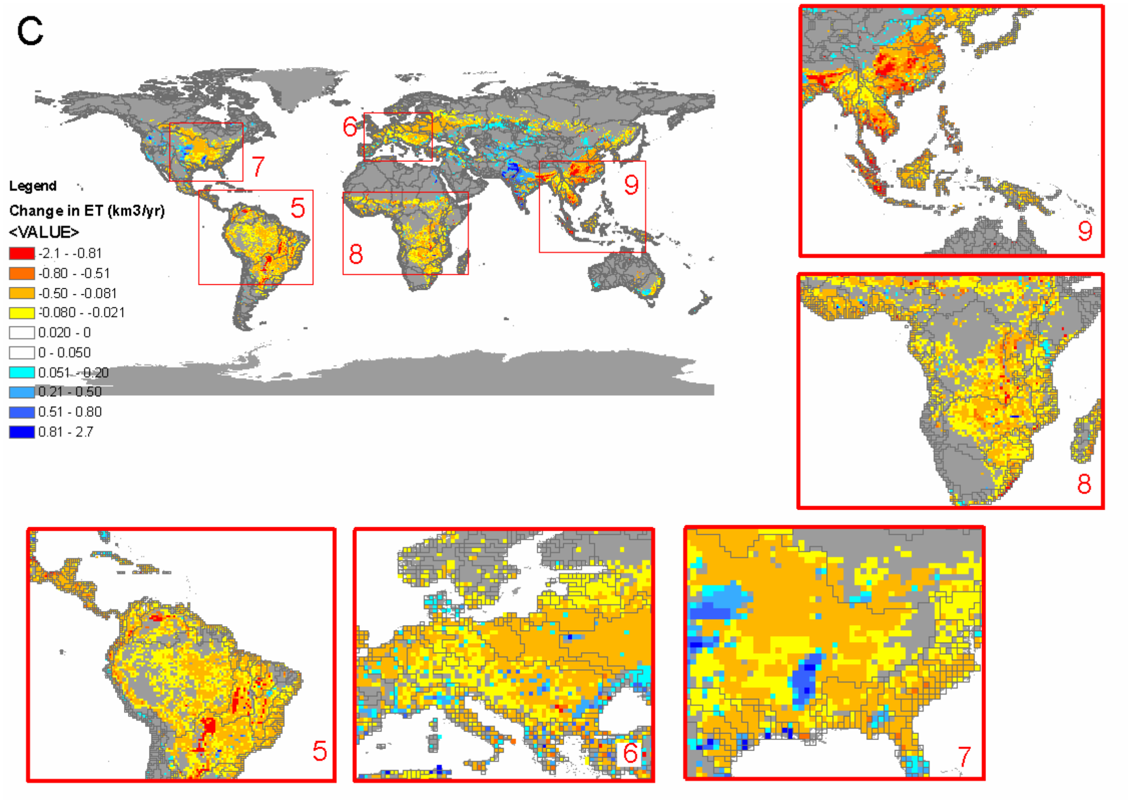


Figure 3.5. a) Change in Annual ET (km^3/yr/ 0.5 degree cell), as a sum of all land cover transformations; b) areas of predominately increased ET. c) areas of predominately decreased ET. 30 minute resolution, all HLCs included: irrigated agriculture, non-irrigated agriculture, grazing, built-up lands, and reservoirs.

There are four major zones of increased ET, for which irrigated agriculture is the main source of change (Figure 3.5b). 1) ET is increased in the west-central USA, primarily due to grassland which has been converted to irrigated agriculture (likely from the fossil Ogallala aquifer), supplemented by conversion of open shrubland, closed shrubland and desert to built-up land and reservoirs. 2) ET is increased in north-western India and southern Pakistan, primarily due to conversion of closed shrubland, open shrubland and desert areas to irrigated agriculture. 3) ET is increased in south-west Australia, primarily due to conversion of savannah and closed shrubland to irrigated agriculture. And 4), ET is increased in southern Kazakhstan, Uzbekistan and Tajikistan where open shrubland, savannah, tundra, closed shrubland and desert have been converted to irrigated agriculture; these areas lie in the drainage basin for the Aral Sea.

The locations of areas of increased ET, and possibly of reduced runoff, are all located in areas of severe water-stress, as identified by Vorosmarty et al. (2000) who incorporated the influence of population in defining areas of severe water scarcity to be those for which the domestic, agricultural and industrial demand of water exceeds 40% of the discharge of the local rivers. All four regions of increased ET overlap with areas where a high number of people live in areas of severe water scarcity.

There are five extensive zones of decreased ET, for which grazing land and non-irrigated agriculture are the main HLC sources of change (Figure 3.5c): 5) ET is decreased in northern south-America, primarily due to conversion of wetlands, savannah and evergreen broadleaf forest to grazing land and non-irrigated agriculture, and to a lesser extent these land types being converted to built-up lands. 6) ET is decreased in Europe, where deciduous broadleaf forest has been converted to grazing land, non-irrigated agriculture and built-up land. 7) ET is decreased in the central USA where forest, savannah and grassland have been converted to a suite of grazing land, non-irrigated agriculture and built-up land. 8) ET is decreased in sub-Saharan Africa, where evergreen broadleaf forest, wetlands and savannah have been converted to non-irrigated agriculture and grazing land, and to a lesser extent, built-up land. And finally, 9) ET is decreased in South-East Asia where wetlands, evergreen broadleaf forest has been converted to non-irrigated agriculture and grazing land.

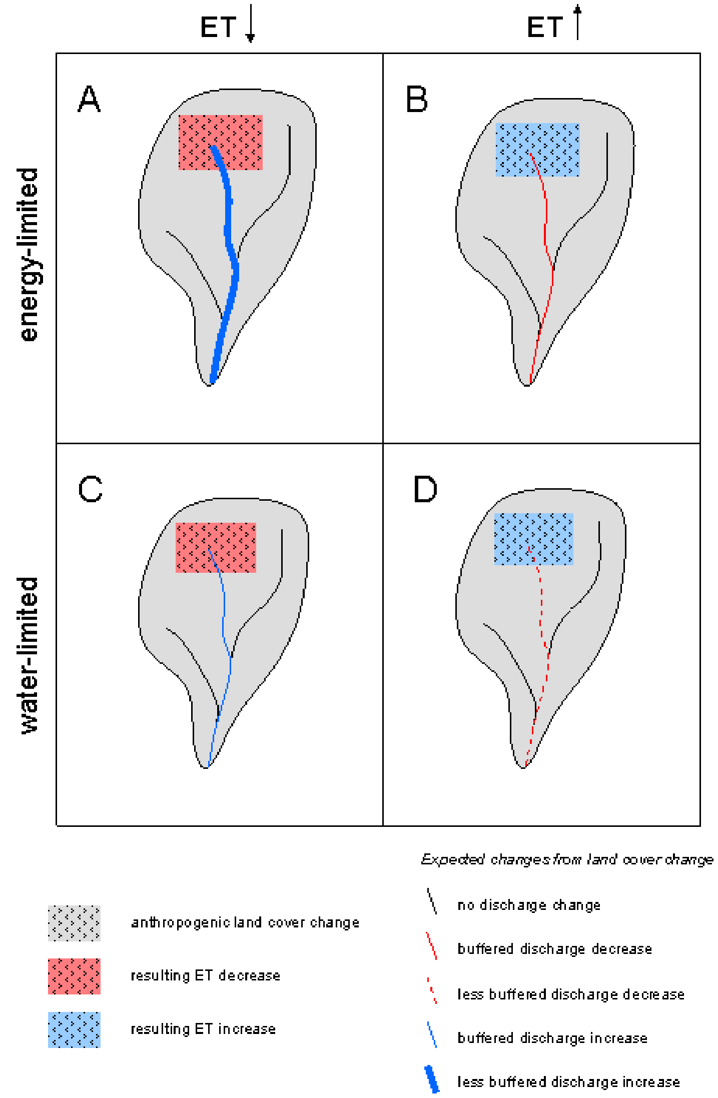
Regions 1, 2, 7, and 8 (Figure 3.5 b,c) overlie with regions of strong coupling between soil moisture and precipitation for boreal summers, as simulated with 12 global coupled atmospheric-land surface models (Koster et al. 2004). In such areas with strong coupling, there is an increased likelihood that change in ET would affect precipitation.

Yet fluxes of altered ET do not necessarily directly translate to equivalent or near-equivalent flux changes to other components of the water cycle, such as discharge. I suggest that ET changes can be buffered in space and time, that certain regions can serve as a more effective buffer than others, and I propose a simplified scheme that classifies basins by their ability to buffer the effects of ET change.

Most simply, the ability of regions to buffer impacts of changes in ET is a function of the direction of ET change and the limiting process for ET in the basin, whether energy-limited or water-limited (Figure 3.6). Take, for example, an area where ET is reduced because forest has been converted to grazing land; in arid regions tending towards water-limiting ET, such as in Arizona, the extra surface water created from the reduced ET has a higher likelihood to be re-evaporated, therefore buffering the change, than in areas where ET is more energy-limited, such as in a temperate rainforest in northern California.

Basin (or region) types with a greater ability to buffer ET change are those that have an increase in ET in an energy-limited basin (Figure 3.6b) or a decrease in ET in a water-limited basin (Figure 3.6c). Basins types with a reduced ability to buffer ET change are those that have decrease in ET in an energy limited basin (Figure 3.6a), or an increase in ET in a water limited basin (Figure 3.6d). This proposed buffer scheme is highly simplified, and it does not represent well basins which alternate between moisture and energy limited, such monsoon areas.

Figure 3.6 Capacity of watersheds or regions to buffer ET changes. The largest decreases in discharge from land cover change should occur when ET is increased in arid areas, and the largest increases in discharge from land cover change should occur when ET is decreased in energy-limited areas.



By applying this simple buffer concept to major basins over (125,000 km^2) in the 9 areas of changed ET (Figure 3.5 b, c), and making a first comparison of the total ET change with an estimate of the mean annual discharge of major basins, I make a speculative estimate of major basins with the largest likelihood experience discharge change from land cover change (Figure 3.7).

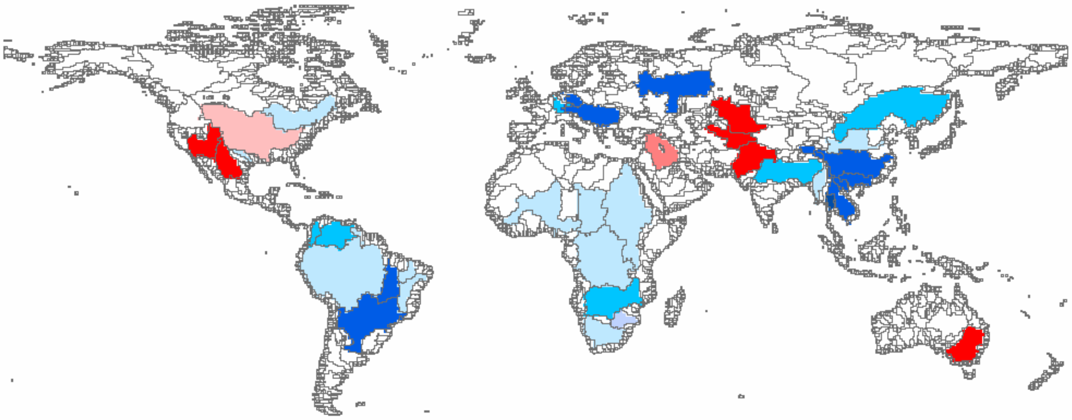


Figure 3.7. Basins in hotspot areas. Dark Red indicates ET increase (>4% of discharge) in a type D basin (Figure 3.6D) where fossil aquifer is not the major source of water for increased ET. Coral indicates 2-4% change in a type D basin where fossil aquifer is not the major source of water. There were no type B basins in the hotspot areas. Pink indicates ET increase > 1% but fossil aquifer is a major source of water for increased ET. Dark blue indicates a greater than 4% change in a type A basin. Medium blue indicates 2-10% change in a type A basin. Pale blue indicates 1-2% change in a type A basin, or an ET decrease in a type C basin. Basins over 125,000 km^2 area in hotspot areas are included in the inventory. Discharge estimates calculated from (Oki et al. 1995)

Basins are classified for buffers based on direction of ET change, and a simple water / energy-limited classification is based upon a classification of basin aridity by

(Revenga et al. 1998), in which a basin is classed as energy-limited if more than 30% of the basin is arid[40], water-limited if less than 30% of the basin is arid.

In this simplified scheme, the major basins with the highest likelihood of land cover change contributing to increased runoff, and possibly flooding are: Elbe, Danube, Volga, Parana, Tocatins. Chang Jiang, Zhujiang, Hong, Mekong, and Chao Phraya. Some of these basins have experienced extreme flooding events in recent years, for example Elbe in 2002 (Tetzlaff et al. 2003), and the Chang Jiang in 1998 (Peng et al. 2005). The major basins with the highest likelihood of land cover change contributing to reduced runoff, and possibly water availability are: Colorado, Rio Grande, Amu Darya, Syr Darya, Indus, and Murray. One of the hotspot regions, the drainage basin of the Aral Sea, has undergone dramatic hydrologic changes since the 1950s losing 50% of its surface area and 66% of its volume, coincident with an increase in the amount of irrigated land has increased by 100%, and in the population in the basin by 140% (Akmansoy and McKinney 1998). This ranking does not include small basins (< 125,000 km^2) where changes to runoff may also be likely.

Flooding risk is also determined by the ability for a basin to buffer change in ET as a function of the connectivity of land cover change. Land cover changes directly connected to the river network (such as urban lands and reservoirs) are less likely to be buffered than those not directly connected to the drainage network. So despite the relatively small contribution of change to ET from urban areas and reservoirs (Table 3.6),

---

[40] aridity index based on the World Atlas of Desertification (UNEP 1992b); arid areas are classified as those for which the ratio between precipitation and potential evapotranspiration is in the range <0.05 – 0.50. Ratios of 0.65 or greater indicate humid zones.

it can be argued that it is important to include these HLCs in studies of land cover change on river flow because of their higher connectivity with the river networks.

3.6 Limitations and Conclusions

This study is limited by the availability of ET data and a major source of uncertainty in this study is in the spatial interpolation of the point estimates of ET to global fields of ET. Spatial interpolation is obviously most uncertain where ET data are sparse, including central Asia and India and Pakistan; unfortunately, this area overlies some “hotspot” areas. Also, the anthropogenic land cover type with the largest change in ET volume across the globe, agriculture and grazing, also has the sparsest data representation per unit area. Further work is recommended to obtain additional year-long ET measurements central Asia and India, and more annual measurements of agricultural and grazed areas. I hope that this project will incite more field-based studies on how land cover change alters the water cycle, which is particularly needed for land cover change involving urbanisation.

The identification of regions and basins most likely to experience change in ET from land cover change is limited because not all global land cover changes could be taken into account. Potential for deforestation to reduce ET in temperate latitudes is under-estimated because rotational clear-cutting of forests could not be considered; for example, this results in an erroneous impression that the boreal forests of Canada and USSR are relatively untouched (Figure 3.2) even though there has been extensive deforestation for wood harvesting in these areas (FAO 1999b). Future work to map global tree plantations and deforested areas not converted to an anthropogenic land cover is important.

Other types of anthropogenic land cover change are not considered; for example, river diversions draining wetlands in Iraq, and areas burned for fuel wood in the tropics. The estimate of changed ET is also conservative because grazing in arid, semi-arid and in grassland biomes was not included in this study, even though this activity can increase albedo, and reduce root structure, surface roughness and LAI , reducing ET (Charney 1975, Hoffmann and Jackson 2000).

Other considerations include that, because annual average estimates of ET are used, this study assumes no temporal trends in ET over the period of observations, and this study is also limited by the quality of the rasters of the land cover distribution (Appendix G).

Future modelling-based studies will be useful to compare with and expand upon this study, as the two approaches have contrasting advantages and limitations. Modelling is useful to estimate how changes in ET are propagated to changes in other components of the water cycle, including precipitation and runoff, and to estimate changes in the water cycle at sub-annual temporal scales, important scales for flooding and water shortages. In contrast to modelling, the advantages of the approach used in this study are: 1) the alterations between individual land covers can be distinguished at a high resolution (5 minute), important so that the potential vegetation in more discrete HLCs (built-up land, and reservoirs) can be identified; 2) a greater suite of land cover types can be included; and 3) attributing the source of changed ET to a particular land cover change is more easily accomplished in GIS than in modelling studies.

This study has furthered our understanding of how land cover change activities alter ET, estimating that of all anthropogenic land covers, grazing and agriculture are currently having the greatest impact on ET. Because of the potentially important role of grazing and agriculture in the hydrologic cycle, it is important that modelling studies advance the quality of parameterisation of these land covers (following (Gervois et al. 2004) for agriculture).

A benefit of this study is that it provides a comprehensive source of local estimates of ET data, useful for validation of remote sensing and modelling estimations of ET, and to place other ET point estimates in context. It is important, for example, to place eddy covariance estimates of ET in context, because of their small area of representation and because the global distribution of flux tower sites is not chosen via a sampling plan, (Baldocchi et al. 2001). Validation of modelled and satellite derived estimates of ET is important as many factors complicate the use of satellite data for ET estimation and independent measurements of water-budget components are essential to validate simulation models and empirical equations (Brye et al. 2000b).

This study sets the framework for a comparison of various causes to observed water cycle changes, whether from climate change or land cover change. In the future it will be important to compare predicted changes to ET from present land cover change with those from climate change to see where the effects are synergistic and where they might cancel out.

This study identifies nine areas of the globe with the most extensive changes to ET, and allows for a preliminary estimate of where land cover change may contribute to increased flooding or water shortages. These “hotspots” correlate with previously identified water stressed areas. Particular attention to monitoring of ET, runoff, and land cover change is recommended for the “hotspot” areas. The hotspots do not always correspond with the areas with the most extensively modified land cover (Figure 3.2a), because some land cover changes tend to alter ET more strongly than others. The hotspots for increased ET are located where irrigated agriculture has replaced drylands. The hotspots for decreased ET are located where there have been large areas of forest and wetlands converted to grazing, non-irrigated agricultural lands or built-up lands.

By mapping direction, strength and location of ET change across the globe from the current extent of anthropogenic land cover change, this study provides the first documentation of how the current extent of anthropogenic land cover change can alter global ET patterns, allowing for a speculative estimate of areas where land cover change may be impacting the presence of increased flooding or water shortages. In this way, this study advances our understanding of how anthropogenic land cover change might be acting to contribute to the global water crisis.

Appendix A. Database of Land Cover Area Estimates

Table A1: Global agricultural area (A_{ag})

Source	Area	Notes
Amthor *et al*.,1998	14.8 x 10^{12} m^2	modified secondary
DeFries & Los, 1999 Loveland *et al*., 2000	13.94 x 10^{12} m^2	area in IGBP DISCover Product; AVHRR satellite data
FAO, 1990, 1991	14 x 10^{12} m^2	4700 x 10^6 ha is used by humans, 30% of this is devoted to crops, including tree crops as well as annual row crops
FAOSTAT, 2000	15.1 x 10^{12} m^2	arable and permanent crops; for 1998, country survey
Hansen *et al*., 2000	11.1 x 10^{12} m^2	University of Maryland 1 km project; AVHRR satellite data
Houghton, 1999	1360 x 10^6 ha	synthesis of records
Klein Goldewijk, 2001	1,477,600 E+03 ha	compilation of secondary information, http://arch.rivm.nl/env/int/hyde/
Lal & Pierce, 1991	1.5 billion ha	area of arable land cultivated to produce food
Ramankutty & Foley, 1998	17.92 x 10^6 km^2	represents the area in croplands during the early 1990s for each grid cell on a global satellite 5 min resolution latitude-longitude grid; combined a satellite-derived land cover data set with a variety of national and subnational agricultural inventory data; uses adjusted FAO data from Alexandratos 1995; does not include plantations and shifting cultivation
Strahler, 2002	14,671,396 km^2	croplands from the "Consistent Year Product"
Tilman *et al*., 2001	1.54 x 10^9 ha	
Warnant *et al*., 1994	13.4 x 10^{12} m^2	using CARAIB mechanistic model
WRI, 2000	27,890,000 km^2	global agricultural area
Wood *et al*., 2000 WRI, 2000	36,234,000 km^2	based on PAGE ecosystem boundaries, defined independently; for agricultural areas
WRI, 2003	1501452.0 x 10^3 ha	arable and permanent crops
WBGU, 1998	16.0 x 10^6 km^2	global cropland area

Table A2. Global annual anthropogenically-burned land area not including burning on other occupied land classes (A_b)

Source	Area	Notes
Levine *et al*., 1995	175 million hectares	for burning on savannah areas; not including burning on other classes such as A_{tp}, A_{ho}, A_{gz}

Table A3. Global built-up areas (or human occupied land) (A_{bu} or A_{ho})

Source	Area	Notes
Amthor *et al*., 1998	2.0 x 10^{12} m^2	modified secondary, http://www-eosdis.ornl.gov/NPP/other_files/worldnpp1.txt
WRI, 2000	256,332 km^2	WRI, 2003
Hansen *et al*., 2000	260,092 km^2	p. 1350, table 4. based on 1 km resolution from the AVHRR
Loveland, 2000	260,117 km^2	p. 1320, table 8
Strahler, 2002	243,617 km^2	urban and built up area in "Consistent Year Product"
WRI, 2000	4,745,000 km^2	p. 260. defined by the NOAA/NGDC night time lights of the world database (IGBP data); the location of stable lights
Wackernagel *et al*., 2002	275,102,000 ha	online supplemental database; land for settlement and infrastructure

Table A4. Global grazing land area (A_{gz})

Source	Area	Notes
FAO, 2000	3,476,886,000 ha	
FAO, 1990	3300 x 10^6 ha	70% of 4700 x 10^6 ha (land used by humans) is in permanent pastures)
Klein Goldewijk, 2001	3,450,617 E+03 ha	http://arch.rivm.nl/env/int/hyde/
White *et al*., 2000	3.4 x 10^9 ha	area of forest land converted to grazing land

Table A5. Global impounded water area (A_i)

Source	Area	Notes
St. Louis *et al*., 2000	1.5x10^6 km^2	ICOLD's (International Commission on Large Dams) database

Table A6. Global tree plantation area (A_{tp})

Source	Area	Notes
Winjum & Schroeder, 1997	130,000,000 ha	for 1990; based on Allan & Lanly, 1991
Pandey, 1997 Brown, 1999 Matthews *et al.*, 2000	1.03 million km^2	in recent FAO surveys, industrial wood plantation forests worldwide; for 1995
Pandey, 1995	150 x 10^6 ha	for 1990
Dixon *et al.*, 1994	112 x 10^6 ha	for 1987-1990
Sedjo, 1999	99.3 million ha	drawn from Bazett, 1993; area of industrial plantations worldwide
Sharma, 1992	135 million ha	sum of area of tropical and temperate forest plantations

Table A7. Area of forest permanently cleared for population increase and colonization (A_{fc})

Source	A_{fc} (original units)	Comments
Bull, Mabee & Scharpenberg, 1998	11,269,000 ha/yr	average annual change of forest area as reported in 1996
World Bank, 2000	101,724 km^2/yr	average annual deforestation 1990-1995; the area of permanent conversion of natural forest area to other uses
Andreae, 1990	4.1-10.1 x 10^6 ha/yr	range between Hao *et al.*, 1990 [ref. 54], and Houghton *et al.*, 1985 [ref. 6]; area cleared in primary and secondary forests for permanent use
FAO, 1997	130,000 km^2/yr	annual average global loss of forest in developing countries
Lanly, Singh & Janz, 1991	17 million ha/yr	annual average tropical forest alteration rates from 1981-1990
Dixon *et al.*, 1994	15.4 x 10^6 ha / year	changes of forest area are estimated from a multidecade analysis, spanning 1971-1990
WBGU, 1998	13 million ha/yr	between 1980 and 1995, area of forest converted annually in the tropics

Table A8. Area of forest converted to grazing (A_{gcp})

Source	A_{gcp} (original units)	Comments
FAO, 1990	330 x 10^6 ha	area of land in permanent pastures; reduced by assumed portion of land in permanent pastures that was not previously forested, or presently in human occupied areas

Table A9. Area of savannah (A_s)

Source	A_s (original units)	Comments
Amthor *et al.*, 1998	22.5 x 10^12 m^2	area of tropical savannah; part of GPPDI, review of NPP sites around the globe
Loveland *et al.*, 2000	19,513,990 km^2	for woody savannas and savannas, based on IGBP DISCover data layer
Warnant *et al.*, 1994	20.0 x 10^6 km^2	tropical savannah; for CARAIB model
Andreae, 1990	1530 million ha	area of tropical savannas
Kucharik *et al.*, 2000	5.34 x 10^6 km^2	annual average value for 1965-1994 for IBIS model output
Melillo *et al.*, 1993	20.5 x 10^6 km^2	for tropical and temperate savannah; for TEM model
Prentice & Fung, 1990	5 x 10^12 m^2	areal extents were bioclimatically simulated using observed climatology from Holdridge, 1947
Ramankutty & Foley, 1999	26.71 x 10^6 km^2	for 1990; estimated area of global savannah, grassland, steppes

Table A10. Area cleared in tropical virgin forests by shifting cultivation (A_{sctrf})

Source	A_{sctrf} (original units)	Comments
Vitousek *et al.*, 1986	1.0 x 10^6 ha/yr	based on the average of the range presented by Seiler & Crutzen, 1980 0.5-1.5 x 10^6 ha/yr [ref. 104, p. 218]. Seiler & Crutzen's estimate is calculated from the percent of the population estimated to be migrating that use shifting cultivation (from Watters, 1971 and Conklin, 1962) (2.5 to 7.5 million) multiplied by the average cleared forest area per capita each year (p. 218); this value is obtained from Petriceks [1968] (0.2 ha/capita).
Myers, 1980	7.1x10^6 ha/yr	assumes each family clears 1 ha/year; estimates each family = 7 people; assumes 50 million cultivators occupy primary forests. For 1980, applying to closed forests of the humid tropics (including permanent and temporary clearing).
Hao, Liu & Crutzen, 1990	3.4 million ha/yr	area cleared of virgin forests to shifting cultivation a year; based on Lanly, 1982 [ref. 72]

Appendix B. Database of Biomass Estimates

Table B1. Biomass of forest areas permanently cleared for population increase and colonization (B_{fc})

Source	B_{fc} (original units)	Comments
Vitousek *et al.*, 1986	22.2 kg/m^2	derived from Seiler & Crutzen's, 1980 [ref. 104] estimate of average biomass densities for tropical biomes.
Brown & Lugo, 1982	11-370 t/ha	based on a synthesis of literature data on total forest biomass estimated by direct measurements on experimental plots
Winjum & Schroeder, 1997	81 t(C)/ha	based on review of various studies; for low -moist latitudes; mean carbon storage in above- and below-ground phytomass of artificially established plantations
Ajtay, Ketner & Duvigneaud, 1979	25-42 x 10^3 g/m^2	biomass of tropical forests
Whittaker and Likens, 1973	4-45 kg/m2	mean values for range of forest types
FAO, 1995	169 t/ha	average forest biomass for total developing world; from FORIS database; for developing countries; annual loss of biomass due to deforestation
Dixon *et al.*, 1994	28-174 Mg(C)/ha	carbon densities in forests of the world
WBGU, 1998	78-190 t(C)/ha	unmanaged and managed pine, spruce and birch boreal forests, Finland; adapted from Karjalainen, 1996
Kucharik *et al.*, 2000	5.4-9.1 kg(C)/m^2	for tropical evergreen & deciduous forest, temperate broadleaf & needleleaf evergreen forest, temperate deciduous forest, boreal forest, evergreen/deciduous mixed forest; annual average values
Bargali, Singh & Singh, 1992	7.7-126.7 t/ha	5-8 yr old Eucalyptus hybrid plantation in India
Brown, Gillespie & Lugo, 1991	50-530 Mg/ha	for tropical Asian forests
Burschel, Kursten & Larson, 1993	137-290 t(C)/ha	temperate natural beech forest and production beech forest, Slovakia
Cannell, Dewar & Thornley, 1992	230-380 t(C)/ha	temperate old deciduous forest, and temperate 80 year old plantation, Europe
Fang *et al.*, 1998	84 Mg/ha	area-weighted mean biomass density for all the forests of China, derived from biomass-volume relations
Harmon & Hua, 1991	206-976 Mg/ha	for forests in China and Oregon; based on Xu ZhengBan *et al.*, 1985, and Grier & Logan, 1977
Lakida, Nilsson & Shvidenko, 1997	10.36 kg/m^2	average phytomass in forest vegetation of European Russia (including the Urals); from 1993 FSA inventory of European Russia; total phytomass in forest vegetation of forested areas
Lodhiyal & Lodhiyal, 1997	12.2 - 112.8 t/ha	above and below-ground biomass - India poplar plantation, 1-4 year old
Reichle *et al.*, 1973	8.32 x 10^3 g(C)/m^2	temperate deciduous forest
Lodhiyal, Singh & Singh, 1995	84.0-170.0 t/ha	Populus plantation, 5-8 yr old
Schroeder *et al.*, 1997	28-200 Mg/ha	US forests
Delcourt & Harris, 1980	460 Mg/ha	total live biomass for south-eastern US virgin forest
Harmon, Ferrell & Franklin, 1990	259-612 Mg(C)/ha	range in temperate 450-year old spruce forest, and 60-year old spruce plantation, Canada (above and below ground and organic layer and dead wood)
Harmon, Garman & Ferrell, 1996	300-980 Mg/ha	estimated from different size class distributions having the same stocking density and quadratic mean diameter at breast height

continuation of Table B1. Biomass of forest areas

Lanly, 1982; FAO/UNEP, 1981	6-135x10^3 kg/ha	for undisturbed moist, seasonal and dry forest; in tropical America, Asia and Africa, based on volumes of growing stock
Brown & Lugo, 1990	10-250 t/ha	10-60 year-old forests; above-ground, excluding litter; based on graph of assembly of approx 18 sites from Asia, Africa and Latin America
FAO/UNDP, 1972 Brown, 1997	183-240 t/ha (212-278 t/ha above- and below-ground)	above-ground biomass, for secondary moist forest in Nicaragua; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Folster, de las Salas & Khanna, 1976	200 t/ha (232 t/ha above- and below-ground)	above and below ground for tropical moist forest; 16 year old forest; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Honzak *et al.*, 1996	76-222 Mg/ha	mean ± std. Dev. for 6 different estimates on 16 plots in regenerating Brazilian tropical forests
Jankovic, 1969 Brown 1997	20-210 t/ha (23-244 t/ha above- and below-ground)	above-ground biomass for young secondary moist forest in Peru; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Kellman, 1970 Brown & Lugo, 1982	236 t/ha	above and below ground for tropical premontane wet forest; 27 year old
Rollet, 1962 Brown, 1997	70-370 t/ha (81-429 t/ha above- and below-ground)	above-ground biomass for secondary moist forest in Cambodia; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Royal Forest Department of Thailand, 1980 Brown, 1997	190-530 t/ha (220-615 t/ha above- and below-ground)	above-ground biomass for secondary moist forest in Sri Lanka; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Lucas *et al.*, 1996	175 Mg/ha	for mature Brazilian tropical forests
Rodin & Bazilevich, 1967(Rodin and Bazilevitch 1967)	15-75 kg/m^2	for tropical rain forest
Brown & Lugo, 1980	57-182 t(C)/ha	range of organic carbon storage in tropical forests
Fearnside, 2000	39.8-463 t/ha	for unlogged tropical forest and cerrado present in Brazil's Legal Amazon region in 1990; converted to above- and below-ground biomass assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Folster, 1989; WBGU, 1998	77-333 t(C)/ha	carbon stocks of primary forests, semi-natural forests, secondary and managed forests
Brown Gillespie & Lugo, 1989	141.94-192.2 Mg/ha	for closed tropical broadleaf forests based on volumes - total tropics
Brown & Lugo, 1984	60-690 t/ha	range of biomass density for a variety of tropical forests
Hingane, 1991	9.6-12.5 x 10^3 g/m^2	in Indian forests
Ciesla, 1995	25-100 t(C)/ha	average above-ground stored carbon, based on biomass values from Olson *et al.*, 1983
Houghton, 1991	27-250 t(C)/ha	biomass for tropical moist, seasonal, closed, woodlands
Jiang *et al.*, 1999	432 - 487.64 Mg/ha	for seasonal rainforests and rainforests in China; based on empirical data sets, remote sensing, and climate-vegetation models; biomass is an average for plot-based measurements
Art & Marks, 1971	3905-68200 g/m^2	for natural coniferous, hardwood and tropical stands
Brown & Iverson, 1992	20-560 Mg/ha (23-650 above- & below-ground)	total aboveground biomass in wet forests of tropical America; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Whittaker & Likens, 1975a,b Whittaker, 1975	6-80 kg/m^2	normal range of biomass (dry matter) for tropical rain forest and tropical seasonal forest

continuation of Table B1. Biomass of forest areas

Kira & Ogawa, 1971	288-493 t/ha (334-572 (above- and below-ground)	indirect estimation of biomass of south-east Asian rainforest; for tropical rainforest; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]
Melillo *et al.*, 1996	85-200 t(C)/ha	for closed tropical forests in, Africa, Asia and Latin America using direct biomass measurements (average of evergreen and seasonal forest vegetation carbon)
Rodin, Bazilevich & Rozov, 1975	260-650 t/ha	global range from boreal to tropical forests
Palm, Houghton & Melillo, 1985	40-250 t(C)/ha	for undisturbed tropical rainforest
Matthews, 1984	1340.1 Pg / 39.3 x 10^12 m^2	carbon inventories derived from ecosystem areas estimates from different data sources
Seiler & Crutzen, 1980	15-39 kg/m^2	average biomass densities of tropical rainforests and second-growth tropical forests
SCEP, 1970	1012 x 10^9 t(C) / 48 x 10^6 km^2	forest and woodland; from FAO yearbooks, 1951-1969, Ryther 1969, Olson, 1970, and Whittaker and Likens (unpublished at the time)
Birdsey, 1992	51-98 Mg(C)/ha	average biomass of forests in different regions of USA
Sohngen & Sedjo, 2000	126-292 Mg(C)/ha	average vegetation per hectare from nine regions considered in model, including temperate, emerging and tropical areas; from assembly of studies conducted in the 1990s.
Ruimy, Dedieu & Saugier, 1996 Olson, Watts & Allison, 1983	12 kg(C)/m^2	combined a vegetation map with estimated mean carbon content per vegetation type to produce a map of total biomass; does not include cultivation; use Olson et al., 1983 data set in their model
Lieth, 1975	45-75 kg/m^2	for tropical rain forest
Olson, Pfuderer & Chan, 1978	8-18 kt(C)/km^2	estimated carbon pool in boreal and tropical forests
Tomich *et al.*, 1997	295 t(C)/ha	above-ground biomass and roots & rhizomes for dipterocarp forest
Olson, Watts & Allison, 1983	5-16.9 kg(C)/m^2	above- and below-ground for tropical all-year moist young degraded secondary forest
Houghton, Hackler & Lawrence, 2000	78 - 200 Mg(C)/ha	average biomass of forests in different regions of USA

Table B2. Biomass of savannah (including below-ground) (B_{scs})

Source	B_{scs} (original units)	Comments
Ajtay, Ketner & Duvigneaud, 1979; WBGU, 1998	29 t(C)/ha	not including carbon in soil; for tropical grasslands
Amthor *et al.*, 1998	2930 g(C)/m^2	part of GPPDI, review of NPP sites around the globe
WRI, 2000	405-806 Gt(C) / 52,554,000 km^2	data for grasslands from PAGE 2000 dataset
Kucharik *et al.*, 2000	2.4 kg(C)/m^2	annual average biomass for savannah biome for IBIS model; 1965-1994
Hao, Liu & Crutzen, 1990	21-80 t/ha	for open non-fallow forests, range from Brown & Lugo, 1984; Detwiler *et al.*, 1985
Whittaker & Likens, 1975	0.2-15 Pg/x 10^12 m^2	normal range of biomass for savanna
Whittaker & Likens, 1973	1.8 kg(C)/m^2	assumes carbon content approximates dry matter x 0.45
Olson, Pfuderer & Chan, 1978	7 kt/km^2	estimated carbon pool for woody savannah & scrub

continuation of Table B2. Biomass of savannah

Tomich *et al.*, 1997	30 t(C)/ha	in SE Asia, *Imperata* degradation; may include trees; above-ground and roots & rhizomes
Olson, Watts & Allison, 1983	3 kg(C)/m^2	tropical savannah and woodland.
Alder, 1982, Brown, 1997	28 t/ha (32 t/ha above- & below-ground)	aboveground biomass for tree savannah in Gambia, includes trees; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
FAO, 1983	20 t/ha (23 t/ha above- & below-ground)	aboveground biomass for degraded tree savanna; includes trees in Burkina Faso; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]
Faure, 1990	6.5 x 10^3 g/m^2	mean biomass for savanna; 1975
Gaston *et al.*, 1998	5.8 Mg(C)/ha	mean density of grass/shrub savannas carbon pools for grasslands in Africa
Jenkinson *et al.*, 1999	241 g(C)/m^2	a mean of measurements made in January 1980 and 1981 by Deshmukh, 1986 and of measurements in January 1985 and January 1986 by Kinyamario & Imbaba, 1992 ; the mean above-ground biomass (living and dead) and the start of the burning season in Nairobi National Park
Kauffman, Cummings & Ward, 1994	7128-8625 kg/ha (8268-10005 kg/ha above- & below-ground)	mean biomass of fuel load (above-ground biomass) for Brazilian Campo; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Lossaint & Rapp, 1971	26 kg/m^2	for mature chaparral
Marsch, 1976 Brown, 1997	96 t/ha (111 t/ha above- & below-ground)	aboveground biomass, but may include trees; for tree savannah in Benin; based on forest inventories; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]
Menaut et al., 1991	0.5-8 t/ha	range of maximum biomass in West African savannas
de Milde & Inglis, 1974 Brown, 1997	195 t/ha (226 t/ha above- & below-ground)	aboveground biomass for moist savannah forest, includes trees, Surinam; based on forest inventories; use average area of savannah for calculation; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]
ORNL NPP database	100-800 t/ha	for South Africa and Guinean Savanna
Shea *et al.*, 1996	3164-7343 kg/ha (3670-8518 kg/ha above- & below-ground)	total prefire fuel loads for humid and dry Miombo in Zambia and South Africa; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]
Woomer, 1993	48-94 Mg(C)/ha	natural broad-leafed dry savannah in South Africa and miombo woodland in Zimbabwe

Table B3. Biomass of above-ground grasses in burned savannah (B_{sh})

Source	B_{sh} (original units)	Comments
Vitousek *et al.*, 1986; Seiler & Crutzen, 1980	0.65 kg/m^2	from average of the range in Seiler & Crutzen, 1980: 0.5-0.8 kg/m^2. Seiler & Crutzen obtained this range in comparison of data from Rodin & Bazilevich, 1967], Bourliere & Hadley, 1970 , and Batchelder & Hirt, 1966 . I assume Vitousek *et al.*'s value of 0.39 was derived from average of Seiler & Crutzen's range of total herb biomass affected by savannah fires of 3000-4800 Tg/yr; did not use this value in our calculations because units do not correspond.
Matthews, 1984	0.7, 2.8 Pg(C) / 0.8, 6.1 (x 10^{12}) m^2	range biomass of grassland without woody cover
Gonzalez-Jimenez, 1979	6.98-9.15 kg/ha	for grasses in Venezuelan savannas
Miranda *et al.*, 1997	99-251 g/m^2	mean +/- standard deviation; obtained from 12 samples in Brazil
Scholes & Walker, 1993	518-868 g(C)/m^2	above-ground grasses and litter for broad-leafed savannah at Nylsvley
Batchelder & Hirt, 1966	0.6 kg/m^2	for above-ground herb biomass in savannah; summary of data available in the early 1960s
Bourliere & Hadley, 1970	0.1-0.9 kg/m^2	total herb above-ground biomass densities
Coutinho, 1982	5-7 t/ha	above-ground plant biomass of herbaceous undergrowth strata of cerrado in Brazil
Haggar, 1970	3.8 t/ha	for perennial tussock grasses in Nigeria and other savannah zones of tropical Africa
Hopkins, 1965	516 g/m^2	dry weight of herb layer just before burning for savannah in Nigeria
Huntly & Morris, 1982	5.7 t/ha	for savannah grasses in South Africa
Menaut & Cesar, 1982	5.7-8.9 t/ha	above-ground herb biomass in seven facies of West African savannas
San Jose & Medina, 1975 & 1976	5-8.4 t/ha	mean ± standard deviation for grass layer of Venezualan savannas
Singh & Misra, 1978	4.94 t/ha	for savannah grasses in India

Table B4. Biomass of secondary tropical forest (including below-ground) (B_{strf})

Source	B_{strf} (original units)	Comments
Brown & Lugo, 1982	11-90x10^3 kg/ha	for mature fallow tropical forest; based on direct measurements of carbon stocks in vegetation
Winjum & Schroeder, 1997	81 t(C)/ha	based on a review of many studies; for low, moist latitudes; mean carbon storage in above- and below-ground phytomass of artificially established plantations.
Lanly, 1982; FAO/UNEP, 1981	25-90x10^3 kg(C)/ha	for mature fallow tropical forest; based on volumes of growing stock; for vegetation
Brown & Lugo, 1990	10-250 t/ha (11.6-290 with roots)	excluding litter; based on graph of assembly of approx 18 sites from Asia, Africa and Latin America (added root component by assuming a root to shoot ratio of 0.16) [Brown & Lugo, 1984]

continuation of Table B4. Biomass of secondary tropical forest

FAO/UNDP, 1972 Brown, 1997	183 t/ha (212 t/ha above- and below-ground)	converted to above- and below-ground by assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984]; for secondary moist forest in Nicaragua; based on forest inventories
Folster, de las Salas & Khanna, 1976	200 t/ha (232 t/ha above- and below-ground)	above and below ground for tropical moist forest; 16 year old forest; below-ground biomass estimated using root/shoot ratio of 0.16) [Brown & Lugo, 1984; ref. 90]
Honzak *et al.*, 1996	76-222 Mg/ha	mean ± std. Dev. for 6 different estimates on 16 plots in regenerating Brazilian tropical forests
Jankovic, 1969; Brown 1997	20-195 t/ha (23-226 above- and below-ground)	converted to above- and below-ground by assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]; above-ground biomass for late secondary moist forest in Peru; based on forest inventories
Kellman, 1970; Brown & Lugo, 1982	236 t/ha	above and below ground for 27 year old tropical premontane wet forest.
Rollet, 1962; Brown, 1997	190 t/ha (220 above- and below-ground)	converted to above- and below-ground by assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90] above-ground biomass for secondary moist forest in Cambodia; based on forest inventories
Royal Forest Department of Thailand, 1980; Brown 1997	280 t/ha (325 above- and below-ground)	converted to above- and below-ground by assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90] above-ground biomass for secondary moist forest in Sri Lanka; based on forest inventories
Lucas *et al.*, 1996	175 Mg/ha (203 above- and below-ground)	converted to above- and below-ground by assuming a root to shoot ratio of 0.16 [Brown and Lugo, 1984]; for 30-year old forest plot
Rodin & Bazilevich, 1967	15 kg/m^2	for an 18-year old moist tropical forest
Brown & Lugo, 1980	63-117 t(C)/ha	vegetation only (does not include soil)
Fearnside, 2000	34.3-90.5 t/ha (39.8-105 above- and below-ground)	converted to above- and below-ground biomass assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]. Data assumes growth rate of secondary forest aboveground live biomass; based on FAO, 1996
Folster, 1989; WBGU, 1998	77-127 t(C)/ha	for 18 year old forest, tropical moist, seasonal and Dipterocarpaceae forests, in Africa, America and SE Asia
Brown, Gillespie & Lugo, 1989	141.94 Mg/ha	above and below-ground estimates of logged closed tropical broadleaf forests based on volumes, from Brown and Lugo, 1984
Olson, Watts & Allison, 1983	5 kg(C)/m^2	above and below ground for tropical all-year moist young degraded secondary forest
Fearnside, 1994; Fearnside, 2000	415 t/ha	above & below ground; for areas felled in 1990, after adjustment for location of clearings within the region and for removal of biomass by logging
Fearnside, 1997	35.6-50.5 t/ha	calculated from residence time and growth rate

Table B5. Biomass of tropical forests (including below-ground) (B_{trf})

Source	B_{trf} (original units)	Comments
Brown & Lugo, 1982	46-183 t(C)/ha	for undisturbed seasonal forest; in tropical America, Africa and Asia, based on direct measurements of carbon stocks; for six forest categories
Ajtay, Ketner & Duvigneaud, 1979	25-42 x 10^3 g/m^2	for tropical humid and seasonal forests
FAO, 1995	169 t/ha	from FORIS database; for all tropical regions

continuation of Table B5. Biomass of tropical forest

Dixon *et al.*, 1994	99-174 Mg(C)/ha	weighted densities for low latitude forests, compilation of other sources
WBGU, 1998	50-186 t(C)/ha	
Kucharik *et al.*, 2000	5.4-9.1 kg(C)/m^2	for 1965-1994
Lucas *et al.*, 1996	225-563 Mg/ha (261-653 above- & below-ground)	range of estimates of total above-ground biomass for mature primary forests at Manaus, Brazil; recalculated with roots (assuming a root to shoot ratio of 0.16) [Brown & Lugo, 1984; ref. 90]
Rodin & Bazilevich, 1967	75 kg/m^2	for tropical rain forest
Brown & Lugo, 1980, 1992	240-563 Mg/ha	based on forest inventories
Fearnside, 2000	463 t/ha	for unlogged tropical forest in Brazil's Legal Amazon region in 1990
Fearnside, 2000	433.6 t/ha	Amazonian forest
Folster, 1989	141-333 t(C)/ha	
Brown Gillespie & Lugo, 1989	149.6-192.2 Mg/ha aboveground (173.5-223 above- & below-ground)	recalculated with roots (assuming a root to shoot ratio of 0.16) [Brown & Lugo, 1984; ref. 90]; for closed tropical broadleaf forests based on volumes
Brown & Lugo, 1984	105.3 t/ha	weighted average carbon density for unlogged tropical forests (open and closed); from reports by FAO; 76 countries covered, using forest stand volumes
Brown & Lugo, 1984	78.1-689.7 t/ha	range of biomass for a variety of tropical forests; compilation of other sources
Hingane, 1991	9.6-12.5 x 10^3 g/m^2	for Indian forests; from compilation of other sources
Houghton *et al.*, 2000	145-232 Mg(C)/ha	average biomass of Brazilian tropical forest for two methods of calculation, one from RADAMBRASIL data, and one from a conversion of RADAMBRASIL stem-wood volumes to biomass
Ciesla, 1995	50 - 100 t(C)/ha	based on biomass values from Olson *et al.*, 1983 [ref. 116]
Houghton, 1991	89-250 t(C)/ha	range of biomass for tropical closed forests; compilation of other sources
Jiang *et al.*, 1999	432.18 - 487.64 Mg/ha	using empirical data sets, remote sensing, and climate-vegetation models; biomass is an average for plot-based measurements; for seasonal rainforests and rainforests in China
Art & Marks, 1971	17166-41500 g/m^2	for tropical rain forest - for trees, shrubs and herbs, above and below ground; compilation of other sources
Brown & Iverson, 1992	20-560 Mg/ha	total aboveground biomass in wet forests of tropical America
Whittaker & Likens, 1975; Whittaker, 1975	6-80 kg/m^2	normal range of biomass (dry matter) for tropical rain forest and tropical seasonal forest
Kira & Ogawa, 1971	288-493 t/ha (334-572 (above- and below-ground)	indirect estimation of biomass of south-east Asian rainforest; for tropical rainforest; belowground estimated assuming a root to shoot ratio of 0.16 [Brown & Lugo, 1984; ref. 90]
Melillo *et al.*, 1996	165-200 t(C)/ha	for closed tropical forests in, Africa, Asia and Latin America using direct biomass measurements (average of evergreen and seasonal forest vegetation carbon)
Melillo *et al.*, 1996	85-110 t(C)/ha	for closed tropical forests in Latin America, Asia and Africa using biomass estimates from volume from 1980s; based on data from [Brown & Lugo, 1984; ref. 90], Palm *et al.*, 1986, and Hall & Uhlig, 1991
Rodin, Bazilevich & Rozov, 1975	600-650 t/ha	phytomass of tropical humid forest
Palm, Houghton & Melillo, 1986	90-250 t(C)/ha	for undisturbed tropical rainforest

continuation of Table B5. Biomass of tropical forest

Matthews, 1984	249.1 Pg(C) / 12.3 x 10^12 m^2	total biomass of tropical rainforest
Sohngen & Sedjo, 2000	14-166 Mg(C)/ha	average vegetation per hectare for emerging and tropical forests; from assembly of studies conducted in the 1990s
Ruimy, Dedieu & Saugier, 1996	12 kg(C)/m^2	combined a vegetation map with estimated mean carbon content per vegetation type to produce a map of total biomass; does not include cultivation; use Olson *et al.*, 1983 data in their model
Whittaker & Likens, 1973	16-20 kg(C)/m^2	assumes carbon content approximates dry matter x 0.45
Lieth, 1975	45-75 kg/m^2	tropical rain forest mature biomass; compilation of other sources
Olson, Pfuderer & Chan, 1978	17-18 kt(C)/km^2	estimated carbon pool in tropical forests
Tomich *et al.*, 1997	365 t(C)/ha	peak carbon stocks for dipterocarp forest
Fearnside, 1997	434 t/ha	pre-logging total biomass for forests cleared in 1990; is derived as a weighted average from estimates that are disaggregated by state and forest type; for Brazilian Amazonia
Whittaker, 1970	45000 g/m^2	
Lechthaler, 1956 Lucas *et al.*, 1996	563 Mg/ha (653 above & below ground)	recalculated with roots (assuming a root to shoot ratio of 0.16) [Brown & Lugo, 1984]; total above-ground biomass for moist closed forests near Manaus
Edwards & Grubb, 1977	350 t/ha	above and below ground for undisturbed New Guinean rainforests
McWilliam *et al.*, 1993	175.8-366.8 Mg/ha (203.9-425.4 above & below-ground)	total aboveground biomass (mean +/- standard deviation) for 4 quadrats in a mature forest at Manaus, Central Amazon, Brazil; recalculated with roots (assuming a root to shoot ratio of 0.16) [Brown & Lugo, 1984];
Rodrigues, 1967; Lucas *et al.*, 1996	275 Mg/ha (319 above & below-ground)	recalculated with roots (assuming a root to shoot ratio of 0.16) [Brown & Lugo, 1984]; total above-ground biomass for moist closed forests near Manaus
Medina & Cuevas, 1989	337-562 Mg/ha	above- and below-ground biomass for nutrient limited Amazonian tropical forests
Ovington, 1965	27090 g/m^2	tropical rainforest average for trees, herbs and shrubs

Appendix C. Estimates of Net Primary Productivity

IGBP biomes are abbreviated as follows:

OS	Open shrublands	EN	Evergreen needleleaf
GS	grassland	EB	Evergreen Broadleaf
CS	Closed Shrublands	M	mixed
WS	Woody Savannahs	DB	Deciduous Broadleaf
SA	Savannahs	DN	Deciduous Needleleaf

Table C1. Productivity of agricultural lands (PR_{ag})

Source	PRag	Notes
Ajtay, Ketner & Duvigneaud, 1979	700-1600 g/m^2/yr	
Amthor *et al.*, 1998	425 g(C)/m^2/yr	part of GPPDI, review of NPP sites around the globe; Values for all biomes except northern peatlands are for the top 1.0 m of soil only; from ORNL website http://www-eosdis.ornl.gov/NPP/other_files/worldnpp1.txt
Field *et al*, 1998	8 Pg(C)/yr	1982-1990. Carnegie-Ames-Stanford approach (CASA) to analyse satellite data; cell size of 1^{o} x 1^{o}. converted estimate of NPP 8 Pg/yr to Pg/m^2/yr by dividing it by mean A$_{ag}$
Hingane, 1991	875 g/m^2/yr	
Houghton & Skole, 1990 Olson, Watts & Allison, 1983	0.76 Pg/T10^{12}m^2/yr	updating Olson et al 1983 productivity using new cropland area
Malmstrom *et al.*, 1997	247.5-412.4 g(C)/m^2/yr	mean values for 1982-1990; for grains only
Potter *et al.*, 1993	89-487 g(C)/m^2/yr	mean +/- standard deviation for cropland production
Prince & Goward, 1995	468 g(C)/m^2/yr	mean value used a cell size of 64 km^2
SCEP, 1970	6 x 10^9 t(C)/yr/ 15 x 10^6 km^2	intermediate values from secondary sources (FAO yearbooks 1951-1969, Ryther, 1969 Olson, 1970, Whittaker and Likens, unpublished)
Schmitt, 1965	1.5 x 10^{17} kcal(C)/10 million km^2	application of multiplicative reduction factors to the insolation of the amount of energy received outside the atmosphere; Schmitt, 1965, p. 670, conversion of 5 kcal / gOM
Vitousek *et al.*,1986	0.94 Pg/10^{12}m^2/yr	modified from Ajtay *et al.*, 1979
Warnant *et al.*, 1994	771 g(C)/m^2/yr	using CARAIB model
WBGU, 1998	25 Gt(C)/yr	crops, arable and permanent pasture
Whittaker & Likens, 1975; Whittaker, 1975; Lieth, 1975; Lieth, 1973	100-4000 g/m^2/yr	
Whittaker and Likens, 1973a	644 g/m^2/yr	approximate mean of global range of values; predicted from mapping precipitation and temperature; updated from Lieth, 1964 ; mean NPP for the world around 1950
Whittaker and Likens, 1973b	290 g(C)/m^2/yr	mean NPP
Woomer, 1993	1.8-9.75 Mg/ha/yr	maize fields in Zimbabwe, Mozambique, and Cote d'Ivoire

Table C2. Productivity of lands converted to pasture (PR_{gcp})

Source	PR_{gcp} (original units)	Comments
Vitousek *et al.*, 1986	1.41 Pg /(10^12 m2 yr)	assumes the average productivity of derived grazing land is the same as woodlands, grasslands, and savannah; based on data in Ajtay *et al.*, 1979
Ajtay, Kentner & Duvigneaud, 1979	1750 g/m^2/yr	area weighted mean for four savannah types
Ajtay, Kentner & Duvigneaud, 1979	780 g/m^2/yr	area weighted mean for two temperate grassland types
Whittaker & Likens, 1973; Lieth, 1973	500-800 g/m^2/yr	range of average productivity for woodland, grassland, chaparral for around 1950
Potter *et al.*, 1993	5-693 g(C)/m^2/yr	mean +/- standard deviation for perennial grasslands and broadleaf shrubs with grasslands
Amthor *et al.*, 1998	350-790 g(C)/m^2/yr	tropical savannah, grassland and chaparral; part of GPPDI, review of NPP sites around the globe
Kucharik *et al.*, 2000	0.24-0.35 kg(C)/m^2/yr	range of productivity for grasslands and savannah
Rodin, Bazilevich & Rozov, 1975	4-16 t/ha/yr	range of productivity for woodlands, grasslands and savannah; updating of Rodin & Bazilevich, 1967
SCEP, 1970	36 x 10^9 t(C) / 48 x 10^6 km^2	for forest and woodland, grassland and tundra
Whittaker & Likens, 1973	225-315 g(C)/m^2/yr	for woodland and shrubland, savannah and temperate grassland
Whittaker, 1975	600-900 g/m^2/yr	for woodlands, savannah & temperate grasslands
Lieth, 1975	650 g/m^2/yr	average of mean NPP for woodland and shrubland, savannah, and temperate grassland
Olson, Watts & Allison, 1983	0.3-0.57 Pg /(10^12 m^2 yr)	for savannah, woodland and grassland
Woomer, 1993	3.32-8.5 Mg/ha/yr	for miombo woodland in Zimbabwe, coastal forest in Mozambique and Guinean savannah in Cote d'Ivoire (above-ground)
Gonzalez-Jimenez, 1979	2.17-5.29 g/m^2/day	for Venezuelan savannas
Miranda *et al.*, 1997; WBGU, 1998	1 to 10 t(C)ha/yr (mean of 4.5)	range of tropical grasslands and savannah for Brazil
Scholes & Walker, 1993	542-1359.8 g/m^2/yr	95% confidence intervals for broad-leafed savannah at Nylsvley (best long-term estimate). Confidence intervals are based on twice the interannual standard deviation.
FAOSTAT, 1999	278-3580 g/m^2/yr	for permanent pasture; difference between maximum and minimum biomass, sum of positive increments on successive sampling dates, sum of all changes in biomass and losses due to mortality, above ground only; in Africa and India
Prince & Goward, 1995	280-645 g(C)/m^2/yr	GLO-PEM estimates; for grassland and wooded grassland
Delmas *et al.*, 1991	8.5-19.8 t/ha	range of average NPP from satellite data of woodland and tree and shrub savannah and savannah steppe in Africa
Foley, 1994	0.248-0.793 kg(C)/m^2/yr	area-weighted NPP for tropical dry forest and savannah and warm grass and shrub
Goetz *et al.*, 1999	280-640 g(C)/m^2/yr	for 1987; range of means of NPP for wooded grassland and grassland from GLO-PEM, as derived from satellite observations
Hall *et al.*, 1995	120 to 816 g/m^2/yr	range of mean production (above- & below-ground) for ten grassland sites across the world
Lieth, 1972	100-2000 g/m^2/yr	range of grassland and chaparral for 1950
Milchunas & Lauenroth, 1993	103-411 g/m^2/yr	for grasslands; from review of 127 sites from literature sources around the world; above-ground NPP; range within one standard deviation of the mean; aboveground

continuation of Table C2. Productivity of forests converted to pasture

Parton *et al.*, 1995	95-684 g/m^2/yr	range of simulated mean annual above- and below-ground plant production in seven grassland biomes; using CENTURY model for 31 sites (total for all biomes)
Raich *et al.*, 1991	620-1950 g/m^2/yr	for South American grassland and savannah as predicted by Terrestrial Ecosystem Model
Riedo, Gyalistras & Fuhrer, 2000	0.46 to 0.67 kg(C)/m^2/yr	simulated at three different grassland locations; grazing by lactating cows, using PaSim - the mechanistic pasture simulation model.
Sala *et al.*, 1988	100-700 g/m^2/yr	temperate grasslands; 9500 sites in central USA; above-ground
Sims & Singh, 1978	54-523 g/m^2/yr	temperate grasslands; ten western and central North American grassland sites
Van Dyne *et al.*, 1978	126.3-3396.0 g/m^2/yr	range reported for grassland communities; above-ground only; data from review of IBP projects
Ambasht, Maurya & Singh, 1972	1420-3810 g/m^2/yr	grassland in India; above- & below-ground
Choudhary, 1972	650-1060 g/m^2/yr	grassland in India; above- & below-ground
Gupta, Saxena & Sharm, 1972	180 g/m^2/yr	grassland in India; above- & below-ground
Singh, 1968(Singh 1968)	790 g/m^2/yr	grassland in India; above- & below-ground
Singh & Yadava, 1972	2980 g/m^2/yr	Indian grassland
Singh & Yadava, 1974	3538 g/m^2/yr	above- & below-ground net primary production in tropical grassland

Table C3. Productivity of built-up lands (PR_{ho} or PR_{bu})

Source	PR	Notes
Amthor *et al.*, 1998	100 g(C)/m^2/yr	part of GPPDI, review of NPP sites around the globe
Duvigneaud, 1972	0.5 kg/m^2/yr	

Table C4. Productivity of tree plantations (PR_{tp})

Source	PR	Notes
Ajtay, Kentner & Duvigneaud, 1979	1750 g/m^2/yr	
Ajtay, Kentner & Duvigneaud, 1979	0.148-0.429	FAO data; normalising estimates by year and m^3, for trees only
Amthor *et al.*, 1998	670 g(C)/m^2/yr	
Art & Marks, 1971	202-4480 g/m^2/yr	trees, herbs and shrubs
Jiang *et al.*, 1999	10.6-10.7 Mg/ha/yr	China; derived from measured data, remote sensing and Chikugo model
Lugo, Brown & Chapman, 1988	1.6-29.8 t/ha/yr	from range of secondary sources; above-ground net biomass production for species grown for maximum biomass in the tropics; for 1976-1985
Matthews *et al.*, 2000	5-20 m^3/ha/yr	range from tropical species, converted using 625-750 kg/m^3 (p. 457 of Hao *et al.*, 1990)
Winjum & Schroeder, 1997	1.91-17.0 t/ha/yr	range of averages from high latitude, mid-latitude, low-dry and low-moist latitudes forest plantations; used conversions on page 157

Table C5. NPP of firewood (NPP_{fwd})

Source	NPP_{fwd} (original units)	Comments
FAO, 1995a	1830 million m^3/yr	assuming wood density of 0.58 g/cm^3; woodfuel data based largely on estimates derived from scattered 1960s household consumption surveys, which are updated annually in line with population and income growth; for globe
Andreae, 1990, 1991	1260-1430 Tg/yr	mean of population-based and FAO estimates
Hao, Liu & Crutzen, 1990	680 Tg/yr	for 1975-1980
Matthews *et al.*, 2000	1.8 billion m^3/yr	amount of wood burned directly as fuel each year; converted using 625-750 kg/m^3 (p. 457 of Hao et al., 1990, ref. 54)
Crutzen & Andreae, 1990	300-600 Tg(C)/yr	total carbon released from firewood in the tropics
FAOSTAT, 1999	1,721,619,250 m^3	for 1998; converted with wood density of 0.58 g/cm^3; woodfuel data based largely on estimates derived from scattered 1960s household consumption surveys, which are updated annually in line with population and income growth; for globe
Worldwatch Institute, 1996 Tucker, 1999	1,590,000,000 m^3	converted with wood density of 0.58 g/cm^3; for 1991
Hao & Liu, 1994	620 Tg/yr	using data base for spatial and temporal distribution biomass burning with a resolution of 5 degrees of latitude; for late 1970s
Winjum, Brown & Schlamadinger, 1998	515 Tg/yr	for globe; based on FAO 1990 data
Hao, Liu & Crutzen, 1990; FAO, 1987	91.2 x 10^7 m^3/yr	the amount of fuelwood produced from coniferous and non-coniferous forests; convert using 625 kg/m^3 (p. 457 of Hao *et al.*, 1990)

Table C6. NPP eaten by livestock (NPP_{lse})

Source	NPP_{lse} (original units)	Comments
Vitousek *et al.*, 1986	2.2 Pg/yr	from comparing other sources; used conversion of 1cal = 5 g dry matter; from comparison of Wheeler *et al.*, 1981, FAO, 1983 and Pimentel *et al.*, 1980.
Wright, 1990 FAO, 1987	101.0 x 10^18 J/yr	world livestock energy consumption; compilation of other sources
Wheeler, 1981	8.71 x 10^9 Mcal/yr	based on data 1967-1977; required metabolizable energy; used conversion of 1 cal = 5 g
FAO, 1983	0.5 Pg/yr	grain used to feed the livestock worldwide in the early 1980s
Subak, 1999	4.3 kg/head/day	assumptions for pastoral subsistence in Sahelian pastoral system; converted using livestock numbers - 3,388,151,000 head (p. 34, White et al., 2000)

Table C7. Total terrestrial NPP (*TNPP*)

Source	TNPP	Notes
Alexandrov *et al*., 1999	50-70 Gt(C)/yr	based in part on Lieth, 1975
Amthor *et al*., 1998	59 Gt(C)/yr	part of GPPDI, review of NPP sites around the globe
Cramer *et al*., 1999	44.4-66.3 Pg(C)/yr	process-based terrestrial model of ecosystem dynamics (Hybrid v3.0)
Esser *et al*., 1994	44.3 Pg(C)/yr	HRBM 3.0 model
Field *et al*., 1998	56.4 Pg(C)/yr	satellite measurements
Foley, 1994	62.1 Gt(C)/yr	DEMETER, a process-based model driven by observed, monthly mean climate data
Friedlingstein *et al*., 1999		uses CASA model that calculates NPP as a product of APAR
Friend, 1995 Friend *et al*., 1997	39.9 Pg(C)/yr	HYBRID 3.0 model
Haxeltine & Prentice, 1996(Haxeltine and Prentice 1996) Haxeltine *et al*., 1996	54.2 Pg(C)/yr	BIOME 3 model
Kaduk & Heimann, 1995	61.1 Pg(C)/yr	SILVAN model
Kergoat, 1998	62.5 Pg(C)/yr	KGBM model
Kleidon & Heimann, 1998	76.9 Gt(C)/yr	
Knorr, 2000	62.7 Gt(C)/yr	
Kohlmaier *et al*., 1997 Kindermann *et al*., 1993 Ludeke *et al*., 1994	49.9 Pg(C)/yr	FBM 2.2 model
Kucharik *et al*., 2000	110-122.2 Pg/yr	IBIS-2: a dynamic global ecosystem model
McGuire *et al*., 1995 McGuire *et al*., 1998	46.2 Pg(C)/yr	TEM 4.0
Melillo *et al*., 1993	53.2 Pg(C)/yr	process-based Terrestrial Ecosystem Model (TEM), using long term climate data. Plant respiration is a function of the mass of vegetation carbon and air temperature [VEMAP, 1995]
Parton *et al*., 1993	53.3 Pg(C)/yr	CENTURY 4.0 model
Plochl & Cramer, 1995 a, b	49.2 Pg(C)/yr	PLAI 0.2
Potter *et al*., 1993 Field *et al*., 1995	48.9 Pg(C)/yr	CASA model
Prince & Goward, 1995	68.97 Pg(C)/yr	GLO-PEM model
Prince, 1991	66.3 Pg(C)/yr	
Ruimy *et al*., 1996	80.5 Pg(C)/yr	TURC model
Running & Hunt, 1993	62.2 Pg(C)/yr	BIOME-BGC model
Sellers *et al*., 1996a,b Randall *et al*., 1996	47.9 Pg(C)/yr	SIB2 model
Warnant *et al*., 1994 Nemry *et al*., 1996	130-144.4 Pg/yr	CARAIB, a mechanistic model estimating NPP of continental vegetation grid of 1x1 degree.
White *et al*., 1999	46.6-49.5 Pg(C)/yr	Hybrid v4.1 and climate output from UK Hadley Center's experiments
White *et al*., 2000	47 Pg(C)/yr	Hybrid v4.1, a nonequilibrium, dynamic, global vegetation model with a subdaily timestep.
Woodward *et al*., 1995	46.4 Pg(C)/yr	DOLY model

Appendix D. Estimates of Proportions of Biomass Transfer

Table D1. Proportion of forest biomass relative to merchantable fraction ($P_{fb/mf}$)

Source	$P_{fb/mf}$	Comments
Vitousek *et al*., 1986	2.10	based on Johnson & Sharpe, 1983 [ref. 169] and Armentano & Loucks [ref. 166]
Armentano & Ralston, 1980	1.75	for temperate zone forests; based on Spurr & Vaux, 1976 and Rodin & Bazilevich, 1967 [ref. 85]
Brown & Lugo, 1992	1.74	for non conifer forests
Schroeder *et al*., 1997	1.0-2.0	for non conifer forests USA, for poletimber and sawtimber
Delcourt & Harris, 1980	1.34	average scalar for merchantable trees, and added 25% for root biomass.
Harmon, Ferrell & Franklin, 1990	1.18	based on PNW 1970s/1980s papers; bolewood only
Harmon, Garman & Ferrell, 1996	1.6-2.2	model estimate of woody residue left; the range represents the percent left on slopes of 0 and 100%. All woody tree parts including the bole, branches and coarse roots were considered.
Lanly, 1982	4.2-19	for broadleaved forests and coniferous stands in Latin America
Brown, Gillespie & Lugo, 1989	1.5-6.0	related ratio to the quadratic stand diameter, 1.5-2.0 for undisturbed forests, and greater than 7.0 for highly disturbed or recovering forests; aboveground only.
Brown & Lugo, 1984	1.4-3.1	for closed and open forests, based on above and below ground biomass
Seiler & Crutzen, 1980	1.4	"industrial wood waste amounts to 30% of roundwood production"
Sohngen & Sedjo, 2000	1.4 - 5.0	obtained from a variety of sources published in the 1990s (see page 156); understory carbon storage is assumed to be 2% of the carbon stored in mature forests [Birdsey, 1992, ref. 106]
Brown, 1997	1.3-1.74	range for conifers and hardwood
Winjum, Brown & Schlamadinger, 1998	1.1-1.5	for developing and developed countries; related to BEF (biomass expansion factor) as discussed in Winjum et al., 1998
Armentano & Loucks, 1984	1.96	measured in temperate deciduous forests
Delcourt, West & Delcourt, 1981	1.25-1.43	separate for hardwoods and softwoods
Guppy, 1984	5-10	for tropical rain forests
Johnson & Sharpe, 1983	1.31-2.7	range of total and merchantable biomass ratios for forest regions in the USA
Johnson & Sharpe, 1983	1.25-8.16	total biomass / tree stem ratios for selected stands in the USA and Canada; range, not including outlier; compilation of other sources
Kauppi, Mielikainen, & Kuusela, 1992	1.4-2.1	for Europe only; ratio of ((other forest biomass)+(stemwood and bark))/(stemwood and bark)
USDA, 1944	1.33	ratio of commodity drain of standing timber to logs, bolts, and cordwood

Table D2. Proportion of firewood met by land clearing and cultivation ($P_{fwd/lc}$)

Source	$P_{fwd/lc}$	Comments
Palm, Houghton & Melillo, 1986	100%	assumption
Seiler & Crutzen, 1980	30%	assumption

Table D3. Proportion of burning on natural grazing lands (P_{bgnl})

Source	P_{gbnl}	Comments
Vitousek *et al.*, 1986	0.43	assumes that burning, like grazing, happens more often on derived than on natural grazing lands

Table D4. Proportion of productive built-up (human-occupied) lands (P_{ho})

Source	P_{ho}	Comments
Ajtay, Ketner & Duvigneaud, 1979	0.40	assumption

Table D5. Proportion of natural pasture grazed by livestock (relative to all grazed pasture lands) ($P_{lgnp/gp}$)

Source	$P_{lgnp/gp}$	Comments
Vitousek *et al.*, 1986	0.50	assumption that half the forage livestock consumed is obtained from derived pastures

Table D6. Proportion of NPP eaten by livestock from natural lands ($P_{lse/nl}$)

Source	$P_{lse/nl}$	Comments
Houghton Lefkowitz & Skole, 1991	87%	based on the intersection of maps of cattle distribution (USDA/FAS, 1958) with two maps of vegetation; for 1985; for Latin America

Table D7. Proportion of firewood harvested but not used every year (P_{nhfwd})

Source	P_{nhfwd}	Comments
Vitousek *et al.*, 1986	0.50	assumption

Table D8. Proportion of savannah burned annually (*P_{sb}*)

Source	P_{sb}	Comments
Andreae, 1990	0.49	750 million ha burned per year [Hao *et al.*, 1990, ref. 54] divided by 1530 million ha (area of tropical savannas)
Hao, Liu & Crutzen, 1990	3-75%	proportion of savannas burned each year
Menaut *et al.*, 1991	0.25-0.8	
Hao & Liu, 1994	0.50	assumption
Delmas *et al.*, 1991	0.75	percent of African savannah burned each year
Eva & Lambin, 1998	0.282	for burning of savannahs in Central Africa, using ATSR data (Along Track Scanning Radiometer)
Koffi *et al.*, 1995	0.018-0.021	using satellite imagery; for Central Africa
Goldammer, 1995	0.3	5 Tm2 / year of savannah burned; divided by average of A_s
Barbosa *et al.*, 1999	0.49	from AVHRR remote sensing of Africa

Table D9. Proportion of shifting cultivation in savannas (*P_{scs}*)

Source	P_{scs} (original units)	Comments
Vitousek *et al.*, 1986	0.43	based on Seiler & Crutzen, 1980 from data published by Watters [1971] Spencer [1966] , Hill & Randell [1968] and Whittlesey [1937]
Lanly, 1982	41%	Estimated that 239 million ha of land that once supported closed forest were in swidden agriculture as of 1980. Estimated open forest area (savanna) under shifting cultivation for the same year to be 170 million ha
Crutzen & Andreae, 1990	25%	of the burning in shifting cultivation, estimated that 75% takes place in tropical secondary forests and the remainder in humid savannas
Brady, 1996	0.41	for open forests; "some 240 million ha of closed forests and 170 million ha of open forests are thought to be involved in some form of shifting cultivation"
Detwiler & Hall, 1988	64-92%	compilation of other information; remainder from primary and secondary shifting cultivation

Table D10. Proportion of shifting cultivation in secondary tropical forest (*P_{scstrf}*)

Source	P_{scstrf}	Comments
Andreae, 1990	80-90%	compilation of other sources
Myers, 1980	64%	90 million of 140 million cultivators are believed to be in secondary tropical forests; not by area but by population; by area it would be 68%
Lanly, 1982; Detwiler *et al.*, 1985	88.0%	assumption that rate at which secondary forest is cleared for cultivation increases in proportion to the annual rate at which primary forest area is added to shifting cultivation; assumption is based on data from Seiler & Crutzen, 1980
Fearnside, 2000	12%	assembly of primary and secondary information; area cleared per year in shifting cultivation in secondary forests 0.291 Tm2; ratio calculated using Mather's 1990 A_{sc} of 2.4 Tm^2/yr;
Crutzen & Andreae, 1990	75%	based on Seiler & Crutzen, 1980
Detwiler & Hall, 1988	64-92%	compilation of other sources

Table D11. Proportion of wood that humans use of tree plantation origin (P_{tp})

Source	P_{tp}	Comments
Brown, 1999; Matthews *et al.*, 2000	22%	estimated percent of the world's industrial roundwood supply originating from tree plantations

Appendix E. Estimates of Annual Actual Evapotranspiration

Methods of estimation of ET in the database range from the use of evaporating pans and lysimeters (Puckridge 1978, Boast and Robertson 1982, Reicosky 1983), to mass budget estimates based on catchment and site water balances, to calculations based on energy budget derivations (Bowen 1926, Brutsaert 1984, Shuttleworth 1993, Rosset et al. 1997), to flux measurements above the canopy using eddy covariance towers (Baldocchi et al. 1988). Other methods include change in stored soil water, or a simple water balance (Dunin 1969, Scotter et al. 1979, McGowan and Williams 1980); and evaporation chamber techniques (Reicosky and Peters 1977, McJannet et al. 1996) (Appendix E). Each method of determining ET is subject to biases and errors, and it has been estimated that any determination carries a minimum uncertainty of 10% (Angus and Watts 1984).

Abbreviated the methods are as follows:

EB	energy balance
WB	water balance
PT	Priestley Taylor
mPT	modified Priestley Taylor
SWB	soil water balance
PM	Penman Monteith
BREB	Bowen-Ratio Energy Balance
LY	lysimeter
EC	eddy covariance
Pan	pan evaporimeter
MM	micrometeorological measurements
TB	thermal balance method
APan	class A pan
BC	Blaney Criddle
Model	modelling
TH	Thornthwaite model
Satellite	satellite
FC	field chamber
RS	remote sensing
Pman	Penman model
LIT	literature review or compilation of secondary information
ECmodel	ecosystem model
CWB	catchment water balance
TRT	
THM	Thornthwaite and Mather method
GCM	General circulation model
PMR	Penman Monteith Rutter model
BKM	Bucket model
DT	Deuterium
ICP	Isotope and Chloride Profiles in the Sediments
RI	Rutter Interception model
VC	Ventilated Chamber Technique
DL	empirical Dalton formula
FR	Force Restore method

Table E1. Annual evapotranspiration of agricultural areas (ET_{ag})

Source	ET	Method	Notes
Abtew & Khanal, 1994	102.4 cm/yr	catchment water balance	Everglades Agricultural Area in South Florida; sugarcane, vegetables, sod, rice, ornamental nursery plants
Akinremi et al., 1996	163, 161, 174, 235, 157, 164, 135, 226, 248, 226, 233, 207, 157, 126, 144, 214, 143, 153, 135, 225, 212, 217, 203, 180 mm/yr	soil water balance model	various crop rotations of wheat
Allen, R.G., 2000	730-800 mm/yr	range ET_o from the FAO-56-PM equation and the 1985 Hargreaves equation (both applied hourly)	cotton near Menemen, Turkey
Allen, R.G., 2000	790-880 mm/yr	range ET_o from the FAO-56-PM equation and the 1985 Hargreaves equation (both applied hourly)	grapes near Gediz River, Turkey
Allen, R.G., 2000	690-770 mm/yr	range ET_o from the FAO-56-PM equation and the 1985 Hargreaves equation (both applied hourly)	cotton near Gediz River, Turkey
Allen, R.G., 2000	1020-1160 mm/yr	range ET_o from the FAO-56-PM equation and the 1985 Hargreaves equation (both applied hourly)	orchard near Gediz River, Turkey
Anac *et al*., 1999	834-899 mm/yr		cotton in Turkey
Arnold & Allen, 1996	608, 617 mm/yr	multicomponent water budget model SWAT, using data from the 1950s of the hydrologic budget	Illinois watersheds: Panther creek basin, 80% corn, oats and soy beans, 20% pasture, woodland and farm lots, 246 km^2; Goose Creek basin, 86% agriculture 14% woodland, pasture and farm lots, 122 km^2
Aslyng, 1960 Kristensen, 1959 Aslyng & Kristensen, 1958 Aslyng & Nielsen, 1960	392 mm/yr		grass plot near Copenhagen
Ayars *et al*., 1999	549, 691, 437, 645 mm/yr	soil water balance	cotton in San Joaquin Valley
Ayars et al., 2003	1.034 m/yr	lysimeter and water balance	Assuming minimal winter ET. For mature O'Henry Peaches, California
Bastiaanssen *et al*., 2002	580, 410, 360, 970, 1400 mm/yr	SEBAL algorithm for NOAA-AVHRR satellite data	cotton, rice, wheat, sugarcane and mangroves in Indus River basin, Pakistan
Bastiaanssen & Bandara, 2001	1321 mm/yr	remote sensing	homesteads with coconuts, papayas, bananas and mangos, in Sri Lanka
Bastiaanssen & Bandara, 2001	1405 mm/yr	remote sensing	rice paddy in Kirindi Oya, Sri Lanka
Bastiaanssen & Bandara, 2001	1312 mm/yr	remote sensing	agricultural wetland in Kirindi Oya, Sri Lanka
Batchelor, 1984	2333 mm/yr	Pman	for rice paddy , calculated using the Penman 1963 equation
Batchelor, 1984	1896 mm/yr	Pman	for rice paddy , calculated using the Modified Penman equation.
Baumhardt & Lascano, 1999	420 mm/yr	soil water balance	cotton in Wellman, Texas
Brye et al., 2000	511, 372, 484, 355 mm/yr	soil water balance	for maize ecosystems, treated by no tillage and by chisel plough
Choudhury *et al*., 1998	639 mm/yr	biophysical process-based model with satellite & ancillary data	cropland
Choudhury *et al*., 1998	467 mm/yr	biophysical process-based model with satellite & ancillary data	cropland

continuation of Table E1. ET of agricultural areas

Choudhury *et al*., 1998	672 mm/yr	biophysical process-based model with satellite & ancillary data	cropland
Choudhury *et al*., 1998	312 mm/yr	biophysical process-based model with satellite & ancillary data	cropland
Choudhury *et al*., 1998	620 mm/yr	biophysical process-based model with satellite & ancillary data	cropland
Choudhury *et al*., 1998	692 mm/yr	biophysical process-based model with satellite & ancillary data	cropland
Choudhury *et al*., 1998	507 mm/yr	biophysical process-based model with satellite & ancillary data	cropland
Cohen *et al*., 2002	1302 +/- 48 mm/yr	Penman-Monteith equation (reference crop ET)	Bet Dagan, Israel
Conley et al., 2001	293, 559, 429, 664 mm/yr	eddy covariance	sorghum (C4) at Maricopa Agricultural Centre, Arizona, for control dry and control wet treatments
Davis, 1983	700 mm/yr		cotton in San Joaquin Valley
Doorenos & Kassam, 1979	330-1737 mm/yr	FAO-33	cotton, rice, wheat and sugarcane
Dunn & Mackay, 1995	554 (SD = 36.5) mm/yr	model, based on Penman-Monteith with Rutter interception	arable land in the Tyne Basin in North East England
Flohn, 1972	168 cm/yr		average for three oases in Southern Tunisia with manifold, multi-layered horticulture
Giambelluca, 1986	1067 (SD = 627) mm/yr	PE conversion by vegetation cover. PE measured by PAN, P48, M(SREA)	sugarcane and pineapple in Oahu, Hawaii
Grimes, 1982	760 mm/yr		cotton in San Joaquin Valley
Haise & Viets, 1957	19.4, 19.7, 20.3, 21.6, 24.2, 23.9, 22.9, 24.8, 28.3, 23.6, 30.4, 30.2 inches/year	n/a	Amarillo experiment station, USDA, Bushland, Texas
Hauser & Gimon, 2004	1514 mm/yr	LY	irrigated Alfalfa in Amarillo station
Hauser & Gimon, 2004	809 mm/yr	LY	irrigated corn in Amarillo station
Home *et al*., 2002	297.7-429.0 mm/yr	conversion of reference crop ET	irrigated okra
Hoffman, 1985	230-580 mm/yr	soil water balance	3 crop rotations with high frequency irrigation, wheat, grain sorghum, lettuce, then oat, tomato and cauliflower, then barley, cowpea and celery; at US Salinity Laboratory in Riverside, California
Hoffman, 1985	1350-1750 mm/yr	soil water balance	variable irrigation frequency, with tall fescue; at US Salinity Laboratory in Riverside, California
Hunsaker *et al*., 1998	852-867, 88-894, 932-939 mm/yr	model, based on AZSCHED and Kincaid & Heermann	cotton in Arizona
Hutmacher et al., 2002	1900 mm/yr	n/a	alfalfa in arid areas
James et al,. 1989	28-45, 34-50, 30-36, 28-34, 24-28, 25-31 inches /acreyr	n/a	for alfalfa, apples with cover crop, onions (dry), potatoes, sweet corn, winter wheat
Kelly, 1954	12.7-24.4 in/yr		range for high and medium moisture conditions for corn and alfalfa
Kergoat *et al*., 2002	883, 933, 891, 956, 923 mm/yr	global vegetation model	grass / crops using CLIM, RAD, STOM, FERT, and MAX simulations
Krestovsky, 1969b Shiklomanov & Krestovsky, 1988	522 (SD 173) mm/yr		crops and fallow in southern taiga subzone of European former USSR
Jin et al., 1999	537-353 mm/yr	evaluated from field experiments in the area	cotton in Wangtong experimental station, Heilonggang region in the East Hebei Plain of north China

continuation of Table E1. ET of agricultural areas

Liu *et al*., 2002	423.5-453.0 mm/yr	lysimeter	irrigated winter wheat and maize, using a large-scale weighing lysimeter, at Luancheng Station in the North China Plain
Liu, Hunsaker *et al*., 2002	403-512 mm/yr	soil water balance, 3 m soil depth	maize grown in loess tableland at Shaanxi, China
Liu & Kotoda, 1998	554.6 mm/yr	Kotoda 1986 and Advection-Aridity (Brutsaert and Stricket, 1979) models, eddy correlation	ploughed land in Heihi River, NW China, middle part of Hexi corridor
Lvovitch, 1979	173 mm/yr		spring wheat, Kamennaya Steppe
Lvovitch, 1979	397 mm/yr		irrigated wheat, southern Trans-Volga
Lvovitch, 1979	450.0 mm/yr		barley field
Machado, 2004	1080.8	n/a	wheat and rotational crops
Mahmood & Hubbard, 2002	694 mm/yr	soil water balance model	irrigated maize in tall grass - short grass transition in Nebraska, USA
Mahmood & Hubbard, 2002	462 mm/yr	soil water balance model	rainfed maize in tall grass - short grass transition in Nebraska, USA
Makino et al., 1999	784.25 mm/yr	modified Penman method	agriculture in Doki river Basin in Shikoku Island, Japan
Mierau, 1974	1018 mm/yr		Everglades Agricultural Area
Mika *et al*., 2001	286-296 mm/yr	micrometeorological measurements, Antal model	watershed in Hungary that is 74% cultivated, basin of the Tisza river
Mo *et al*., 2004	636-1525 mm/yr	process-based distributed model	arid farmland and irrigated crop, Lushi basin, China
Molchanov, 1973	435 mm/yr	water balance	field in Lugansk district of steppe zone of European Russia, may be underestimated (Gidromet, 1976)
Morton, 1983a	420 mm/yr	CRAE model	agricultural land around the Edmonton International Airport
Olivier, 1961	1729 mm/yr	Olivier method	Shambe Swamps, Sudan, papyrus
Olivier, 1961, Shahin, 1985	1265, 964, 1842 mm/yr	Olivier method, Heargreaves formula and Blaney-Criddle formula	Wad-Medani, Sudan, cotton (assuming minimal ET during summer (left dry)
Pattey, 2004, pers comm	715.14 mm/yr		grain corn at Greenbelt Farm
Pereira, 1964	880 mm/yr	catchment water balance	maize in Kimakia catchment
Preito & Angueria, 1999	736, 495, 631 mm/yr		cotton in Argentina
Raymond & Rezin, 1989	0.902-0.917 m/yr	remote sensing, water use rates	agriculture in Parker Valley Southern Arizona
Roberts, 1998	306-409 mm/yr	empirical relations from other studies	arable land in England
Saranga *et al*., 1998	491-566, 349-390 mm/yr	pan, soil water content, budget	cotton in Israel
Sarwar & Bastiaanssen, 2001	610-720, 380-400 mm/yr	SWAP model, soil water balance model	cotton and what in Indus River basin, Pakistan
Scott & Sudmeyer, 1993	471, 458, 430, 420, 346 mm/yr	ventilated chamber technique	crops (lupins, oats, rape, barley and wheat) near Collie in the southwest of Western Australia.
Sene, 1996	261 mm/yr	soil water balance	sparse vine crop in southern Spain (dry region), using a two-component energy combination model
Shahin, 1985	26609, 29769 x 10^6 m3/yr		quantities of water used by crops in 1962 and 1975 in Egypt - all irrigated
Shih & Gascho, 1980	1546, 1824, 1291, 1463 mm/yr		sugarcane grown in the Everglades Agricultural Area
Shih, 1983	1084-1418 mm/yr		Everglades Agricultural Area
Shiklomanov & Krestovsky, 1988	520, 460, 440, 400 mm/yr		winter crops, summer crops, row crops and bare fallow in southern taiga subzone of European former USSR
Soppe, 2000 Ayars & Soppe, 2001	710, 845, 567, 561, 561 mm/yr		cotton in San Joaquin Valley
Styles & Bernasconi,	713-805 mm/yr		cotton in San Joaquin Valley

continuation of Table E1. ET of agricultural areas

1994			
Szilagyi *et al*., 2001	1.7 mm/day	micrometeorological measurements	Altamaha river basin near Doctortown GA; a mix of urban, forest and agriculture areas; average from 1948-1996
Unland *et al*., 1998	1.462 m/yr	micrometeorological measurements, Bowen-Ratio Energy Balance	irrigated crop in Santa Cruz River in southern Arizona
Urassa & Raphael, 2004	1300 mm/yr	n/a	rice Farm, Morogoro, Tanzania
Van Dijk *et al*., 2001	800, 850, 1500 mm/yr	water balance, micrometeorological measurements, literature	irrigated rice fields, rainfed mixed crops, and fallow land in Ciumutuk river catchment, West Java, Indonesia
Wanjura *et al*., 1996	620, 477, 605 mm/yr		cotton in San Joaquin Valley

Table E2. Annual evapotranspiration of burned lands (ET_b)

Source	ET	Method	Notes
Klinge *et al*., 2001	97, 147, 147 mm/yr	soil water model, micrometeorological measurements	cleared and burned rainforest in eastern Amazonia
Santos *et al*., 2003	861.9 mm/yr	eddy covariance	campo sujo savannah in central Brazil
Sumner, 2001	0.993 m/yr	energy budget variation of eddy correlation	Tiger Bay watershed Volusia County, Florida, natural fires on pine flatwood uplands and cypress wetlands; ET increased after burning, logging followed burning

Table E3. Annual evapotranspiration of barren or sparsely vegetated lands (ET_{barr})

Source	ET	Method	Description
Allison & Barnes, 1983	63 mm/yr	DT	Lake Fromme, a normally dry salt lake
Allison & Barnes, 1985	63-170 mm/yr	isotopic and chloride profiles in sediments, and deuterium	Lake Fromme, a normally dry salt lake in Central Australia
Bellot *et al*., 1999	262.1 mm/yr	hydrological model, negative exponential approach	semi-arid Mediterranean area of Ventos (Alicante, Spain)
Berger *et al*., 2001	0.95 feet/yr	Bowen Ratio energy balance, eddy correlation	playa and bare soil in Ruby Lake National Wildlife Refuge Area, Ruby Valley, North-eastern Nevada
Carlson *et al*., 1990	576 mm/yr	lysimeter	bare land on eastern ridge of Rolling Plains resource region, within a 16 ha livestock enclosure, TX
Cochran *et al*., 1988	10 mm/yr	lysimeter	Owens (Dry) lake playa evaporation
Dirnbock & Grabherr, 2000	0-180 mm/yr	compilation of literature, modelling according to Turc-Wendling energy balance model	vegetation on rocky slopes and initial alpine vegetation in Austrian Alps
Frank & Inouye, 1994	164 mm/yr	Thornthwaite model	Hot desert for 11 sites: 1) Helwan, Egypt , 2) Wadi Halfa, Sudan, 3) Alice Springs, Australia, 4) Meekatharra Australia, 5) El Paso Texas, 6) Imperial, California, 7) Parker, Arizona, 8) Phoenix AZ, 9) Victorville California, 10) Chihuahua Mexico, 11) Mendoza Argentina
Frank & Inouye, 1994	256 mm/yr	Thornthwaite model	Cold Desert for 9 sites:1) Astrahan, Russia, 2) Yan'an China, 3) Elko NV, 4) Ephrata WA, 5) Idaho Falls, ID, 6) Milton Freewater OR, 7) Nyssa OR, 8) Cipolleti Argentina, 9) Sarmiento Argentina
Gohre, 1949	178 mm/yr	lysimeter	bare soil in Eberswalde, Germany

continuation of Table E3. ET of barren land

Henning, 1989	5 cm/yr	energy balance	desert area value from atlas
Johnston *et al.*, 1970	270 mm/yr		barren land in Utah, 1950-1953
Johnston 1970	11.28 in/yr	soil water balance	bare soil plot located near head of Parrish Canyon on the Davis County Experimental Watershed near Bountiful, Utah, elevation 8400 feet asl, 1962-1966
Kane *et al.*, 1990	153, 130, 219, 240 mm/yr	water balance over the water year, checked by energy balance, Priestly Taylor	Imnavait Creek, a 2.2 km^2 watershed underlain by continuous permafrost in the Arctic North Slope of Alaska, assume minimal evaporation during winter
Liu & Kotoda, 1998	99.4 mm/yr	Kotoda 1986 and Advection-Aridity (Brutsaert and Stricket, 1979) models, eddy correlation	Gobi Desert, NW China, middle part of Hexi corridor; coarse sand and small pebbles with sparse scrub vegetation
Lopes 1986	10 mm/yr	lysimeter	Owens (Dry) lake playa evaporation
Major, 1963	101 mm/yr	Thornthwaite model	Blythe California, in the hot Sonoran desert
Major, 1963	69 mm/yr	Thornthwaite model	Dzamyn-Ude, Mongolia, in desert
Major, 1963	89 mm/yr	Thornthwaite model	hot desert near Jacobabad, Pakistan
Malek *et al.*, 1990	229 mm/yr	micrometeorological measurements, Bowen-Ratio energy balance	margin and moist playa in eastern Utah
Miller, 1983	75 mm/yr		Polar Desert: plant cover 1-2% of surface
Mocko & Sud, 1998	6.9, 6.8, 2.3, 6.2 W/m2	by energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	for globe, bare soil
Reynolds *et al.*, 2000	22.8 cm/yr	Patch arid land simulator (PALS-FT)	Chihuahuan Desert, Jordana LTER, New Mexico
Rosenzweig, 1968	log 2.10 mm/yr	Thornthwaite model	Creosote bush desert Nye Co, NV, USA
Rosenzweig, 1968	log 2.34 mm/yr	Thornthwaite model	Cool desert sand dunes, near Rexburg, ID
Sammis & Gay, 1979	259, 231, 242 mm/yr	weighing lysimeter	three sites in the Sonoran desert near Tuscon AZ: a large creosote bush, an adjacent stand of creosote bush, and bare soil plots.
Tyler *et al.*, 1997	88 (+/- 22) mm/yr	eddy correlation, microlysimeters, solute profiling methods	salt cemented sand on abandoned lake bed, groundwater near surface
Ullman, 1985	9-28 mm/yr	solute profiling methods	salt-crusted surface of Lake Eyre in south-central Australia, in a dry period; low rate of evaporation was attributed to the reduced albedo of the salt surface
Unland *et al.*, 1996	230, 262 mm/yr	micrometeorological measurements, eddy correlation, BATS model	Sonoran desert near Tuscon Arizona
Unland *et al.*, 1996	0.157 m/yr	micrometeorological measurements, Bowen-Ratio energy balance	cottonwood in riparian area of Santa Cruz River in southern Arizona
Weltz & Blackburn, 1995	645 mm/yr	lysimeter	bare soil La Copita Research Area, eastern Rio Grande plain of Texas

Table E4. Annual evapotranspiration of human built-up areas (ET_{bu})

Source	ET	Method	Description
Aston, 1977(Aston 1977)	1128 mm/yr	pan	Hong Kong
Baumgartner, 1972 Gohre, 1949	356 - 706 mm/yr	lysimeter	short lawn, range from normal to high water level; assumed per year; Eberswalde, Germany
Bell, 1972	736 mm/yr	modeled (Penman basis)	Sidney, Australia
Campbell, 1982	451 mm/yr	not stated	71% of precipitation, annual average precipitation is 635 mm (International Station Meteorological Climate Summary, Version 4.0, 110 years charted; Mexico

			City, Mexico
Christen & Vogt, 2004	300 mm/yr	energy balance	Basel, Switzerland
Dennehy & McMahon, 1987	951, 953 mm/yr	Bowen Ratio-Energy Balance	low-level radioactive waste burial site, continuous hourly measurements of meteorological variables; near Barnwell, South Carolina
Dow & DeWalle, 2000	75 cm/yr (SD 8.7)	catchment water balance	varying levels of development, watersheds range from 5% developed to 88%; 21 watersheds in Eastern USA
Dunn & Mackay, 1995	438 (SD 24.1) mm/yr	model, based on Penman-Monteith with Rutter interception	"conurbations" in the Tyne Basin in North East England
Giambelluca, 1986	689 (SD 336) mm/yr	Potential ET conversion by vegetation cover. PET measured by PAN, P48, M(SREA)	parks, low, medium and high density urban in Oahu, HI
Gohre, 1949	178 mm/yr	lysimeter	for bare soil
Grimmond & Oke, 1986	577.7 mm/yr	water balance model	32% of precipitation; using water balance model; input data derived from measurements conducted at 3 sites, Vancouver BC
Hauser & Gimon, 2004	767, 764 mm/yr	lysimeter	Simulated Landfill in Coshocton Ohio
Healy *et al.*, 1989	626, 648, 728 mm/yr	Bowen Ratio-Energy Balance, water budget, aerodynamic profile	low-level radioactive-waste disposal site near Sheffield, Illinois
Jia *et al.*, 2002	381-471 mm/yr	distributed watershed model	present conditions and for future development scenarios; Chiba Prefecture, Japan
Klohn-Crippen, 1999	264, 355 mm/yr	catchment water balance	40% impervious urban watersheds
Lamourne *et al*, 1994	373 mm/yr	water budget	55% of precipitation, precipitation 679 mm; Johannesburg, South Africa
Lindh, 1978	360 mm/yr	n/a	Stockholm, Sweden
Liu & Kotoda, 1998	432.6 mm/yr	Kotoda 1986 & Advection-Aridity (Brutsaert and Stricket, 1979) models, eddy correlation	urban areas, NW China, middle part of Hexi corridor; coarse sand and small pebbles with sparse scrub vegetation
L'Vovich & Chernogayeva, 1977	400 mm/yr	model	Moscow, Russia
Morton, 1983a	358 mm/yr	CRAE model	urban land around the Edmonton Airport, Alberta Canada
Stephenson, 1994	457 mm/yr	catchment water balance	suburban catchments near Johannesburg, South Africa
Szilagyi *et al.*, 2001	1.7 mm/day	micrometeorological measurements	2 precipitation stations in the 35,224 km^2 Altamaha river basin near Doctortown GA; average from 1948-1996
Thornthwaite & Mather, 1955	509 mm/yr	soil water budget	300 mm depth of water stored in a soil layer at field capacity; Berkeley, California
Thornthwaite & Mather, 1955	730 mm/yr	soil water budget	300 mm depth of water stored in a soil layer at field capacity; Seabrook, New Jersey
Thornthwaite & Mather, 1955	21.02 in/yr	assume soil water budget	median value of actual ET for 25 year period, Hays, Kansas
Thornthwaite & Mather, 1955	23.19 in/yr	assume soil water budget	median value of actual ET for 25 year period; Charles City, Iowa
Thornthwaite & Mather, 1955	23.82 in/yr	assume soil water budget	median value of actual ET for 25 year period, Wooster, Ohio
Thornthwaite & Mather, 1955	33.07 in/yr	assume soil water budget	median value of actual ET for 25 year period; Auburn, Alabama
Thornthwaite & Mather, 1955	31.4 in/yr	assume soil water budget	annual average; Marked Tree, Arkansas
Van der Ven, 1988	179 mm/yr	water balance	23% of annual average precipitation [779.5 mm (WMO)]; Lelystad, Netherlands

continuation of Table E4. ET of built-up land

Table E5. Annual evapotranspiration of natural forest areas (ET_f)

Source	ET	Method	Description
Abdul Rahim & Baharuddin, 1986	1555 mm/yr	catchment water balance	lowland and hilldipterocarp rain forests on granitic substrates in Peninsular Malaysia
ADWR, 1991	1271-1198 mm/yr	Blaney-Criddle	riparian cottonwoods and willow in the San Pedro River Basin, Sierra Vista sub watershed
Allen, 2000	1300-1470 mm/yr	FAO56-PM equation and the 1985 Hargreaves equation	forest in Gediz River, Turkey
Amin *et al*., 1997	1523 mm/yr	weather data satellite imagery	one watershed for one year in a tropical rainforest in Malaysia; Trolak watershed, in the north-east part of the Bernam River basin in the state of Perak
Amoriello & Constantini, 1999	248.7, 313.3 mm/yr	micrometeorological measurements	Beech Forest, Selva Piana 01-ABR1-IP
Amoriello & Constantini, 1999	353.0, 382.1 mm/yr	micrometeorological measurements	Oak Forest, Carrega 05-EMI1-IP
Amoriello & Constantini, 1999	421.8 mm/yr	micrometeorological measurements	Beech Forest, Brasimone 06-EMI2-IP
Amoriello & Constantini, 1999	509.3 mm/yr	micrometeorological measurements	Spruce Forest, Tarvisio, 08-FRI2-IP
Amoriello & Constantini, 1999	388.0, 361.3 mm/yr	micrometeorological measurements	Oak Forest, Monte Rufino, 09-LAZ1-IP
Amoriello & Constantini, 1999	420.3, 407.9, 339.4, 421.4 mm/yr	micrometeorological measurements	Oak Forest, Colognole, 16-TOS1
Amoriello & Constantini, 1999	420.6 mm/yr	micrometeorological measurements	Spruce Forest, Passo Lavaze, 17-TRE1-IP
Amthor *et al*., 2001	304 +/- 20%, 278 +/- 22%; 280 +/- 19% mm/yr	nine ecosystem process models	150 year old black spruce forest in central Canada
Anthoni *et al*., 1999	430 +/- 70, 400+/- 60 mm/yr	eddy covariance and Penman-Monteith model	two years, ponderosa pine forest
Arkley, 1967	17.1 in/yr	model, assumed soil moisture capacity of 6 inches	Williams, Josephine County, Oregon
Baconguis, 1980	1232 mm/yr	water balance for a watertight area of 3.8 ha	Angat, Philippines, lowland rain forest; dipterocarp rain forest
Bailly *et al*., 1974	1295 mm/yr	water balance for 101 ha basin	Perinet, Madagascar; montane seasonal forest
Baker et al., 2003	32-37W/m2/month	eddy covariance tower and SiB2.5 model using micrometeorological data	Chequamegon National Forest; was logged 85 years ago, Wisconsin
Baldocchi, pers comm.	600-620 mm/yr	eddy covariance	oak forest
Barr *et al*., 2000	360 mm/yr	eddy correlation and deep groundwater piezometer	mature boreal aspen forest in Saskatchewan
Barr *et al*., 2000	390 mm/yr	eddy correlation and deep groundwater piezometer	boreal aspen forest
Bastiaanssen & Bandara, 2001	1312 mm/yr	energy balance	mountain forest in Kirindi Oya, Sri Lanka
Batini et al., 1980	910 mm/yr	forests in Wungong Brook catchment, Australia	

continuation of Table E5. ET of forests

Baumgartner & Reichel, 1975	1185 mm/yr	catchment water budget	Amazon basin
Baumgartner, 1972	450 mm/yr	lysimeter	pines & oaks; assumed per year
Bernhard-Reversat *et al*., 1978	1425 mm/yr	n/a	rainforest in Yapo
Bernhard-Reversat *et al*., 1978	1196 mm/yr	n/a	rainforest in Banco (valley)
Bernhard-Reversat *et al*., 1978	1145 mm/yr	n/a	rainforest in Vanco (plateau)
Bidlake *et al*., 1996	1060 mm/yr	Bowen-Ratio Energy Balance	pine flatwood in west-central Florida
Black *et al*., 1996	403 mm/yr	eddy covariance	deciduous aspen stand in Canada during 1994
Blackie, 1979a	1337 mm/yr	water balance for 544 ha Lagan catchment	Kericho, Kenya, montane rainforest
Blackie, 1979a	1240 mm/yr	water balance for 186 ha Sambret headwater area	Kericho, Kenya, Montane rain forest plus bamboo
Blackie, 1979b	1156 mm/yr	water balance for 65.9 ha catchment	Kimakia Kenya, Montane rain forest dominated by bamboo
Blanken *et al*., 2001	401.1, 412.1, 422.8 mm/yr	eddy covariance	even-aged stand of trembling aspen near Prince Albert, Saskatchewan
Bosch & Hewlett, 1982	1180 mm/yr	catchment water balance	pine forest in Alum Creek (WS2)
Bosch & Hewlett, 1982	975 mm/yr	catchment water balance	pine forest in Alum Creek (WS3)
Bosch & Hewlett, 1982	1016 mm/yr	catchment water balance	mixed hardwoods in Coweeta (6) catchment, NC
Bowden, 1968	1090 mm/yr	converted from pan estimate	six stations in St. Croix, Virgin Islands, utilizing all available historical rainfall, temperature, and pan-evaporation data
Brown, 1971 Clay et al., 1974	437 mm/yr	catchment water balance	Juniper-pinyon forest, Beaver Creek (1) catchment
Brown, 1971; Clay et al., 1974	439 mm/yr	catchment water balance	Juniper-pinyon forest, Beaver Creek (3) catchment
Bruijnzeel & Proctor, 1995	1265 mm/yr	catchment and site water balance studies	equatorial lower montane forest with negligible fog incidence
Bruijnzeel & Proctor, 1995	310-390 mm/yr	catchment and site water balance studies	upper montane cloud forest with high fog incidence
Bruijnzeel & Proctor, 1995; Steinhardt, 1979	980 mm/yr	energy balance	lower montane cloud forest with moderate fog incidence; tall forest in Venezuela
Bruijnzeel & Veneklaas, 1998	450-700 mm/yr	n/a	tropical montane cloud forest
Bruijnzeel et al., 1993	695 mm/yr	site water balance	for a stunted lower montane forest on a coastal mountain , may be a transition to low-elevation upper montane cloud forest on the basis of its mossiness and low stature
Bruijnzeel, 1999	275-1380 mm/yr	n/a	for Tropical Montane Cloud Forests; the frequent presence of clouds reduces ET, further reducing potential water stress; range for dwarf cloud forests, to cloud-free lower montane rainforest; estimates based on indirect estimate; Bruijnzeel cautions again
Bruijnzeel *et al*., 1993	695 mm/yr	short-term site water budget measurements conducted during a dry period	stunted lower montane forest on a coastal mountain in East Malaysia, may be a transition to low-elevation upper montane cloud forest

continuation of Table E5. ET of forests

Bruijnzeel, 1990	1430 mm/yr	literature review	tropical lowland forests
Calder *et al*., 1986	1481 mm/yr	Penman-Monteith model	mature secondary rainforest in Janlappa, West Java, Indonesia
Calder, 1976	1090 mm/yr	"natural" lysimeter	Hafren forest of central Wales, at the headwaters of the River Severn, Plynlimon , Powys; contains 26 Norway Spruce trees
Calder, 1982	400 mm/yr	catchment water balance	six year average, forest biome
Calder, 2003	571, 603 mm/yr	HYLUC model	Greenwood Community Forest, conifers in sand & loam soil
Calder, 2003	553, 594 mm/yr	HYLUC model	Greenwood Community Forest, broadleaf in sand & loam soil
Calder, 2003	554, 594 mm/yr	HYLUC model	Greenwood Community Forest, mixed forest in sand & loam soil
Calvo, 1986	366 mm/yr	water balance for 4740 ha basin (water tight)	cloud forest, Rio Macho, Costa Rica
Cheng *et al*., 2002	1039-1195 mm/yr	catchment water balance	LHC-3 and LHC-5 catchment in Taiwan; dense forests of mixed evergreen hardwood species
Cheng *et al*., 2002	1539 mm/yr	catchment water balance	Fu-Shan No 1 watershed
Cheng *et al*., 2002	1198 mm/yr	catchment water balance	PL-11 watershed in Taiwan Taiwanese forests; dense forests of coniferous species on slopes and hardwood species in valley bottoms
Choudhury & DeGirolamo, 1998	1191 mm/yr	biophysical process-based model with satellite & ancillary data	rainforest
Choudhury & DeGirolamo, 1998	1200 mm/yr	biophysical process-based model with satellite & ancillary data	rainforest
Choudhury & DeGirolamo, 1998	1410 mm/yr	biophysical process-based model with satellite & ancillary data	rainforest
Choudhury & DeGirolamo, 1998	488 mm/yr	biophysical process-based model with satellite & ancillary data	taiga forests
Choudhury & DeGirolamo, 1998	460 mm/yr	biophysical process-based model with satellite & ancillary data	taiga forests
Choudhury & DeGirolamo, 1998	360 mm/yr	biophysical process-based model with satellite & ancillary data	taiga forests
Choudhury & DeGirolamo, 1998	359 mm/yr	biophysical process-based model with satellite & ancillary data	taiga forests
Clarke & McCullogh, 1979	717 mm/yr	2/3 is coniferous forest, 1/3 Japanese larch	
Cleverly *et al*., 2002	74 cm/yr	eddy covariance	Tamarix ramosissima; site on Sevilleta National Wildlife Refuge outside of San Acacia, Rio Grande riparian areas, New Mexico
Collinet *et al*, 1984	1465 mm/yr	water balance for 120 ha basin	Tai 1, Ivory Coast; moist semi-deciduous forest
Collinet *et al*, 1984	1363 mm/yr	water balance for 140 ha basin	Tai 2, Ivory Coast; moist semi-deciduous forest
Cornish & Vertessy, 2001	1075 mm/yr (SD 67.3)	catchment water balance	8 different catchments in Karuah Research Area, of Eucalypt forests in New South Wales, Australia
Cornish, 1993	1190 mm/yr	catchment water balance	Eucalypt forest in Crabapple catchment, Karuah in central New South Wales
Costa & Foley, 1997	3.7 mm/day	land surface model	Amazon basin

continuation of Table E5. ET of forests

Costa & Foley, 1999	1384 mm/yr (SD 60.3)	n/a	Amazon basin
de los Santos, 1981	392 mm/yr	water balance for 7.2 ha basin	mossy montane cloud rain forest; Mt. Data, Philippines
Delfs, 1967	579 mm/yr	n/a	spruce forest in Harz Mt.
DID, 1986	1498 mm/yr	water balance for 56 ha basin	Dipterocarp rain forest, basin "C"; Sungai Tekam C, Malaya
DID, 1986	1606 mm/yr	water balance for 38 ha basin	Dipterocarp rain forest, basin "B"; Sungai Tekam B, Malaya
Dietrich *et al*., 1982	1440 mm/yr	water balance for 10-ha basin	mature semi-deciduous moist tropical forest, Barro Colorado, Panama
Dietrich *et al*., 1982	886 mm/yr	water balance for 10-ha basin	dry year in mature semi-deciduous moist tropical forest, Barro Colorado, Panama
Dirnbock & Grabherr, 2000	270-450 mm/yr	compilation of literature, modelling according to Turc-Wendling, an energy balance model	subalpine spruce forest on steep slope and pine tree forest in Alpine Austria
Dirnbock & Grabherr, 2000	270-360 mm/yr	compilation of literature, modelling according to Turc-Wendling, an energy balance model	montane beech forest in Austria
Dirnbock and Grabherr, 2000	270-360 mm/yr	compilation of literature, modelling according to Turc-Wendling, an energy balance model	montane spruce / fir tree / beech forest in alpine Austria
Dow & DeWalle, 1995	40, 35, 42 cm/yr	water balance method	long term mean for three watersheds, for 70 years of data
Dunn & Mackay, 1995	633 (SD 30.7) mm/yr	model, based on Penman-Monteith with Rutter interception	deciduous forest in the Tyne Basin in North East England
Dunn & Mackay, 1995	766 (SD 45.3) mm/yr	model, based on Penman-Monteith with Rutter interception	evergreen needleleaf forest in the Tyne Basin in North East England
Edwards, 1979	1381 mm/yr	water balance for 16.3 ha catchment	montane evergreen forest (67%), scrub and grasses (33%); Mbeya, Tanzania
Elsenbeer *et al*., 1994	1535 mm/yr	n/a	Western Amazonia, Peru
Eltahir & Bras, 1984	3.1 mm/day	ECMWF assimilated data	Amazon basin
Falkenmark, 1989	400 mm/yr	n/a	taiga forest
Federov, 1977	480 mm/yr	energy balance, micrometeorological measurements, lysimeter	tall spruce forest at Valdai station, Russia; Monthly measurements of evaporation were taken during the warmer months, May to October, using lysimeters. For the remaining months (November to April), an estimate of evaporation was calculated using the Budyko (1956) algorithm for potential evaporation
Feller, 1981	620 mm/yr	catchment water balance	south Australia higher elevation mountain ash catchment
Flerchinger *et al*., 1996	570 (+/- 3), 456 (+/- 51) mm/yr	Simultaneous Heat and Water Model (SHAW), detailed physical process model applied to 2 years of data	southwestern Idaho, Aspen, using SHAW model and meteorological measurements
Focan & Fripiat, 1953	1433 mm/yr	site water balance, tensiometers for soil moisture	secondary seasonal evergreen forest; Yangambi, Congo
Foster, 2001 Bruijnzeel, 1999	275-1380 mm/yr	based on indirect evidence	Tropical Montane Cloud Forests; range for dwarf cloud forests, to cloud-free lower mountain rainforest
Franco-Vizcaino *et al*., 2002	390 +/- 122 mm/yr	soil water balance, lysimeter	Jeffry pine forest in Baja Mexico - very arid
Franco-Vizcaino *et al*., 2002	478+/-87 mm/yr	soil water balance, lysimeter	mixed conifer forest in Baja Mexico - very arid

Franco-Vizcaino *et al*., 2002	446 +/- 122 mm/yr	soil water balance, lysimeter	mixed conifer forest in Baja Mexico - very arid
Frangi & Lugo, 1985	845 mm/yr	site water balance (catchment leaking)	alluvial palm forest within lower montane forest in Luquillo experimental forest
Frank & Inouye, 1994	588 mm/yr	model (Thornthwaite)	broadleaf forest, 10 sites
Frank & Inouye, 1994	1363 mm/yr	model (Thornthwaite)	wet tropical forest 10 sites
Frank & Inouye, 1994	413 mm/yr	model (Thornthwaite)	taiga, 11 sites
Frank & Inouye, 1994	543 mm/yr	model (Thornthwaite)	broadleaf-needleleaf forest, 6 sites
Frank & Inouye, 1994	821 mm/yr	model (Thornthwaite)	coniferous-deciduous forest, 5 sites
Franken & Leopoldo, 1984	1641 mm/yr	catchment water balance	annual water budget for Amazon basin
Friend & Cox, 1995	3.12 mm/day	coupled SCM-vegetation model	forest
Friend *et al*., 1997	841, 1319,1387 MJ/m^2/yr	simulated lE from Hybrid v3.0.	simulated lE from Hybrid v3.0. Values are the means of 10 plots over the last 100 years of a 500 year simulation
Galoux *et al*., 1981	546-617 mm/yr	n/a	pine forest in Berlin
Galoux *et al*., 1981	610 mm/yr	n/a	pine forest in Crowthorne
Garcia-Martino *et al*., 1996	1707 mm/yr	GIS, catchment water balance	the entire elevation range in the Luquillo experimental forest in Puerto Rico
Gash & Stewart, 1977	566 mm/yr	n/a	pine forest in Thetford
Gatewood *et al*., 1950	1.829 m/yr	water budget	lower Gila River valley, annual cottonwood water use estimates (riparian); Lower Safford Valley, Arizona
Gilmour, 1975; 1977	1420 mm/yr	water balance for 25.7 ha	South Creek, Babinda, Queensland, Australia; mesophyll vine rainforest
Gonggrijp, 1941b	1170 mm/yr	water balance for 19.2 ha basin	lower montane rain forest, Ciwidey, Indonesia
Grenier, 2004	314.2, 317.3, 346.5, 404.3, 440.3, 366.4, 368, 298 mm/yr	eddy covariance	Hesse Beech Forest
Grenier, 2004	314.2, 317.3, 346.5, 404.3, 440.3, 366.4, 368, 298 mm/yr	eddy covariance	Hesse Beech Forest
Grünwald, 2004	474, 488, 504, 522, 470, 395, 378 mm/yr	eddy covariance	measured above an old spruce forest, filled using mean diurnal courses with a 14-day window
Hafkenscheid, 2000	890-1050 mm/yr	micro-meteorological measurements	Blue Mountains of Jamaica
Helvey, 1973, 1980	442 mm/yr	catchment water balance	forest, Burns catchment, north-central Washington USA
Helvey, 1973, 1980	467 mm/yr	catchment water balance	forest, McCree catchment, north-central Washington USA
Hermann 1970	1265 mm/yr	water balance for "small catchments"	Sierra Nevada, Colombia, lower montane rain forest
Hermann 1970	308 mm/yr	water balance for "small catchments"	Sierra Nevada, Colombia, cloud forest
Hewlett & Hibbert, 1961	793 mm/yr	catchment water balance	mixed hardwoods in Coweeta (22) catchment, NC

continuation of Table E5. ET of forests

Hewlett & Hibbert, 1961	1019 mm/yr	catchment water balance	mixed hardwoods in Coweeta (2) catchment, NC
Hodnett *et al*., 1995	1.2 mm/day	soil water balance	pasture near Manaus Brazil
Holwerda, 1997 Schellekens *et al*., 1998	435 mm/yr	micro-meteorological measurements	low elevation dwarf cloud forest in Puerto Rico
Hoover, 1944	1072 mm/yr	n/a	Oak / Hickory forest in Coweeta
Hoover, 1944	1059 mm/yr	catchment water balance	mixed hardwoods in Coweeta (17) catchment, NC
Hsia & Lin, 1981	850-1200 mm/yr	n/a	forested watersheds in Taiwan
Hudson, 1988	771 mm/yr	n/a	spruce forest in Severn
Humphreys et al., 2003	432, 435 mm/yr	eddy covariance	50-year old 33 m tall coastal Douglas Fir forest
Hutjes *et al*., 1990	1415 mm/yr	model	Tai, Ivory Coast
Hutley *et al*., 1997	1260 mm/yr	soil water budget	tall lower montane forest subject to frequent, low intensity rainfall associated with low cloud in Queensland, Australia
Huttel, 1975	1145 mm/yr	site water balance, ET derived from soil water balance (neutron probe), and from ET Turc minus Ei	moist semi-deciduous forest; Banco 1 basin, Ivory Coast; located on hill crest; dry year
Huttel, 1975	1195 mm/yr	site water balance, ET derived from soil water balance (neutron probe), and from ET Turc minus Ei	moist semi-deciduous forest; Banco 2 basin, Ivory Coast; located on valley bottom
Huttel, 1975	1425 mm/yr	site water balance, ET derived from soil water balance (neutron probe), and from ET Turc minus Ei	moist semi-deciduous forest; Yapo basin, Ivory Coast, located on hill crest
Jetten, 1994	1485 mm/yr	water balance	Guyana
Jipp *et al*., 1998	4.15 mm/day	soil water balance, micrometeorological measurements	mature rainforest 6 km north of Paragominas in the northern Brazilian state of Para
Johnson & Kovner, 1956	779 mm/yr	catchment water balance	mixed hardwoods in Coweeta (19) catchment, NC
Johnson & Kovner, 1956	1207 mm/yr	catchment water balance	mixed hardwoods in Coweeta (3) catchment, NC
Johnston 1970	21.00 in/yr	soil water balance	plot: scrubby aspen clones, located near head of Parrish Canyon on the Davis County Experimental Watershed near Bountiful, Utah, elevation 8400 feet asl
Jolly et al., 1997	683 mm/yr	catchment water balance	forests in Castlereagh catchment in Murray-Darling basin, Australia
Jolly et al., 1997	939 mm/yr	catchment water balance	forests in Goodradigbee catchment in Murray-Darling basin, Australia
Jolly et al., 1997	879 mm/yr	catchment water balance	forests in Mitta catchment in Murray-Darling basin, Australia
Jolly et al., 1997	701 mm/yr	catchment water balance	forests in Murrumbidgee 18 catchment in Murray-Darling basin, Australia
Jolly et al., 1997	714 mm/yr	catchment water balance	forests in Murrumbidgee 21 catchment in Murray-Darling basin, Australia
Jolly et al., 1997	696 mm/yr	catchment water balance	forests in Namoi 8 catchment in Murray-Darling basin, Australia
Jordan & Heuveldop, 1981	1904 mm/yr	catchment water balance	for tropical rain forest
Jordan, 1978	100 mm/yr	water balance	small alpine watershed in British Columbia

Jordan, 1989	1778 mm/yr	n/a	rainforest in San Calos
Kenworthy ,1969	1750 mm/yr	water balance	dipterocarp rainforest in Ulu Gombak
Kergoat *et al*., 2002	389, 429, 372, 469, 408 mm/yr	global vegetation model	cold deciduous forest using CLIM, RAD, STOM, FERT, and MAX simulations
Kergoat *et al*., 2002	0.887, 0.876, 0.846, 0.878, 0.856 mm/yr	global vegetation model	dry deciduous forest using CLIM, RAD, STOM, FERT, and MAX simulations
Kergoat *et al*., 2002	1159, 1258, 1100, 1262, 1119 mm/yr	global vegetation model	broad-leaved evergreen forest using CLIM, RAD, STOM, FERT, and MAX simulations
Kergoat *et al*., 2002	318, 381, 319, 411, 351 mm/yr	global vegetation model	needle-leaved evergreen forest using CLIM, RAD, STOM, FERT, and MAX simulations
Klinge *et al*., 2001	1368 (SD 17) mm/yr	soil water balance, model, Penman	rainforest in eastern Amazonia
Kostin, 1970	541 mm/yr	from energy and water balance estimates	coniferous broad-leaved and broad-leaved forest province (Orel, Mtsensk, Russia). SW of Moscow, in Central Chernozem belt
Kostner, 2001	370-600 mm/yr	sap flow, eddy covariance	beech forests, according to literature reviewed by Peck & Mayer (1996)
Kostner, 2001	300-750 mm/yr	sap flow, eddy covariance	spruce forests according to literature reviewed by Peck & Mayer, 1996
Krestovsky, 1969b	430, 440, 490, 450 mm/yr	n/a	100-140 year old pine and spruce forest in southern taiga subzone of European former USSR
Krestovsky, 1980	585 mm/yr	catchment water balance, Bowen-Ratio Energy-Balance, Micrometeorological measurements	birch and aspen, aged 50-60 years, in the southern taiga subzone in the European former USSR
Krestovsky, 1980	450-490 mm/yr	n/a	spruce and pine forests, aged 100-120 year, in the southern taiga subzone in the European former USSR
Kumagai *et al.,* 2004	945.7+357.3 mm/yr	water cycling model and measured climatic data	tropical rain forest, Lambir Hills National Park, Sarawak, Indonesia
Kuraji & Paul, 1994	1440 mm/yr	n/a	Sapulut Watershed, East Malaysia
Kuraji, 1996	1450.5 mm/yr	catchment water balance	Sapulut Watershed, East Malaysia
Langford *et al*., 1982	620 mm/yr	catchment water balance	Picaninny catchment mountain ash old growth
Langford, 1976	610 mm/yr	catchment water balance	Eucalyptus forest in Graceburn catchment, Australia
Larsen & Concepcion, 1998	2134-2337 mm/yr	n/a	for the entire Rio Mameyes watershed; error at a max is estimated to be 12% (Schellekends et al., 2000, p. 2191).
Law *et al*., 2000	418 +/- 62.5 mm/yr	eddy covariance, micrometeorological measurements	Metolius site in a Research Natural Area, east side of Cascade Mountains; Ponderosa pine forest, 250 yr and some young 45 year old
Law et al., 2000	436 +/- 65 (wet year) and 400 +/- 60 (dry year (mm)	eddy covariance, Micrometeorological measurements	it is not exactly ET but LE (water vapour exchange). Check to see if it is equivalent
Law, 1957	421 mm	lysimeter	woodland in Hodder catchment
Ledger, 1975	1146 mm/yr	water balance for a 870 ha basin	seasonal evergreen forest; dry season of 5 months; 13% occupied by artificial lake; Guma, Sierra Leone
Leopoldo *et al*., 1981a	1548 mm/yr	catchment water balance for a basin of 2350 ha	Bacio Modelo, Brazil; ET may be too high [Bruijnzeel 1990]

continuation of Table E5. ET of forests

Leopoldo *et al*., 1982b	1675 mm/yr	water balance for 130 ha basin; P determined with one gauge; change in soil water storage neglected; probable catchment leakage	"terra-firma" Amazonian primary forest; using catchment water budget technique; Ducke reserve, Brazil
Leopoldo *et al*., 1993	2.3-4.6 mm/day	n/a	mature forest in ABRACOS project near Manaus, Amazonia
Leopoldo *et al*., 1995	1493.1 (CV 2.08%) mm/yr	catchment water balance, modified Penman method	Amazonian rainforest near Manaus
Lesack, 1993	1120 mm/yr	catchment water budget	central Amazonian primary forest
Lewis, 1968	490 mm/yr	catchment water balance	Oak woodland forest, Placer county catchment
Lieth & Solomon, 1985	100.73 mm/yr	GOES digital imagery, Turc 1954 model	Arrow Creek near Creston BC, unlogged
Lloyd & Marques-Filho, 1988	1120 mm/yr (16-25% uncertainty)	water balance for undisturbed rainforest in central Amazon over 1 year	Central Amazonia, Brazil
Lockwood, 1976	1750 mm/yr	catchment water balance	Sungai Gombak, Malay Peninsula
Loescher et al., 2002	1892, 2294, 2230 mm/yr	n/a	Central American Tropical Wet Forest , calculated from eddy covariance using Priestly Taylor equation
Löfgren, 2004a,b	409, 414, 463, 501, 412, 522 mm/yr	micrometeorological measurements	Station SE15 Kindla, Norway Spruce, Trees have been felled for charcoal to be used in the neighbouring furnace since the 16th century. At the IM site eight "charcoal bottoms" have been traced, several of them with remnants of cabins.
Löfgren, 2004a,b	385, 440, 439, 510, 444, 268 mm/yr	micrometeorological measurements	Station SE16, Gammtratten, Norway Spruce, Biggest trees felled around 1900. Light grazing by cattle up to the 1950´s
Low & Goh, 1972	1516 mm/yr	water balance for an area of 6810 ha	for lowland and hilldipterocarp rain forests on granitic substrates in Peninsular Malaysia; Sungai Lui, Malaya (13% rubber plantations)
Luxmore, 1983	655 mm/yr		oak forest
L'vovitch, 1979	880 mm/yr	n/a	subtropical and tropical eastern broad-leaved wet forests near the ocean
L'vovitch, 1979	780 mm/yr	n/a	subtropical and tropical wet monsoon forests near the ocean
L'vovitch, 1979	800 mm/yr	n/a	equatorial perennially wet evergreen forests (hylean)
L'vovitch, 1979	500 mm/yr	n/a	mountain wet monsoon forests near the ocean
L'vovitch, 1979	400 mm/yr	n/a	taiga forests
L'vovitch, 1979	500 mm/yr	n/a	temperate mixed forests
L'vovitch, 1979	400 mm/yr	n/a	taiga forests
Major, 1963	618 mm/yr	model (Thornthwaite)	forest in Great Smoky Mountains, TN, USA
Major, 1963	1132 mm/yr	model (Thornthwaite)	Calcutta, India, monsoon deciduous forest
Major, 1963	1156 mm/yr	model (Thornthwaite)	Rangoon, Myanmar, mangrove forest
Major, 1963	860 mm/yr	model (Thornthwaite)	Haiti forests

continuation of Table E5. ET of forests

Major, 1963	774 mm/yr	model (Thornthwaite)	Bombay forests
Major, 1963	1665 mm/yr	model (Thornthwaite)	tropical forests near Singapore
Major, 1963	388 mm/yr	model (Thornthwaite)	Arkangelsk, former USSR forest, northern taiga forest
Major, 1963	322 mm/yr	model (Thornthwaite)	Crater Lake, Oregon (1974 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	436 mm/yr	model (Thornthwaite)	Paradise Mountain, Rainier, Washington USA (1690 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	248 mm/yr	model (Thornthwaite)	Gem Lake, California, USA (2780 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	236 mm/yr	model (Thornthwaite)	Ellery L, California, USA (2930 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	1003mm/yr	model (Thornthwaite)	tropical and subtropical dry broadleaf forests near Acapulco, Mexico
Malmer, 1993	1835 mm/yr	n/a	Sipitang, East Malaysia
Marengo *et al*., 1994	1616 mm/yr	annual water budget	Amazon Basin
Marengo *et al*., 2001a	1581 mm/yr	annual water budget	Amazon Basin
Marques *et al*., 1977	1000 mm/yr	micrometeorological measurements, model (Thornthwaite, Penman 48)	Amazon basin, for stretch between Belem and Manaus
Marques *et al*., 1980	1261 mm/yr	micrometeorological measurements, model (Thornthwaite, Penman 48)	annual water budget for Amazon basin
Matsuyama, 1992	3.1 mm/day	water balance	Amazon basin
Mo *et al*., 2004	567 mm/yr	process-based distributed model	Broadleaf forest, Lushi basin, China
Mo *et al*., 2004	593 mm/yr	process-based distributed model	Coniferous forest, Lushi basin, China
Mocko & Sud, 1998	63.1, 59.9, 39.9, 49.7 W/m^2	energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	global scale
Mocko & Sud, 1998	136.5, 116.8, 88.9, 99.7 W/m^2	energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	global scale
Mocko & Sud, 1998	34.9, 29.5, 24.0, 20.5 W/m^2	energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	global scale
Mocko & Sud, 1998	61.1, 52.1, 41.3, 45.2 W/m^2	energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	global scale
Mocko & Sud, 1998	28.0, 25.6, 24.5, 18.8 W/m^2	energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	global scale
Molchanov, 1963	431 mm/yr	n/a	oak forest in Lugansk
Molchanov, 1963	295 mm/yr	n/a	pine forest in Volgograd

continuation of Table E5. ET of forests

Molchanov, 1963	596 mm/yr	n/a	pine / spruce forest in Minsk
Molchanov, 1963	329 mm/yr	n/a	spruce / pine forest in Vologda
Molchanov, 1963	448 mm/yr	n/a	pine spruce forest in Orekhovo
Molchanov, 1963	410 mm/yr	n/a	oak / pine forest in Voronezh
Molchanov, 1963	401 mm/yr	n/a	spruce / birch forest in Sareevo (in Vologda district)
Molchanov, 1963	406 mm/yr	n/a	spruce birch forest in Istra
Molchanov, 1963	378 mm/yr	n/a	spruce elm forest in Kalinin
Molchanov, 1963	286 mm/yr	n/a	pine birch forest in Arkhangelsk
Molchanov, 1973	250-370 mm/yr (Avg 300)	water balance	80-160 year old spruce forest of northern taiga
Molion, 1975	3.1 mm/day	climatonomical	Amazon basin
Moran & O'Shaughnessy, 1984	841 mm/yr	catchment water balance	34 year old Eucalypt tree plantation forest in Monda 1-3 catchments, Australia
Morton, 1983a	956 mm/yr	catchment water balance	forests in Sanguere, Cameroon
Morton, 1983a	1328 mm/yr	catchment water balance	forests in Lagan catchment
Morton, 1983a	1291 mm/yr	catchment water balance	forests in Sambret catchment
Mulholland, pers. comm.	620 mm/yr	catchment water balance	oak forest
Murai, 1980(Murai 1980); Tsukamoto, 1992	801 mm/yr	n/a	Fagus Natural Forest Site in Shizuoka County, Central Japan
Murakami *et al*., 2000	546 mm/yr (SD 75.2)	catchment water balance	mature Japanese cypress and cedar forests
Nakano, 1967	859 mm/yr	catchment water balance	pinus densiflora in Minanmitani catchment
Nakano, 1967	823 mm/yr	catchment water balance	pinus densiflora in Kitatani catchment
National Park Service, 1982	1061 mm/yr	n/a	moist (assumed mixed) forest in Big Thicket National Preserve, Texas
Nijssen & Lettenmaier, 2002	422, 437, 458 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	mature aspen in the White Gull Creek Basin, Saskatchewan, Canada
Nijssen & Lettenmaier, 2002	250, 240, 243 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	mature jack pine in the White Gull Creek Basin, Saskatchewan, Canada
Nijssen & Lettenmaier, 2002	315, 320, 324 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	mature black spruce in the White Gull Creek Basin, Saskatchewan, Canada
Nijssen & Lettenmaier, 2002	387, 398, 411 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	mixed forest in the White Gull Creek Basin, Saskatchewan, Canada
Ni-Lar-Win, 1994	1204 mm/yr	catchment water balance	Niger catchment
Ni-Lar-Win, 1994	1200 mm/yr	catchment water balance	Feredougouba catchment
Ni-Lar-Win, 1994	1127 mm/yr	catchment water balance	Boa catchment
Ni-Lar-Win, 1994	1199 mm/yr	catchment water balance	Bafing catchment

continuation of Table E5. ET of forests

Ni-Lar-Win, 1994	1295 mm/yr	catchment water balance	N'zo catchment
Ni-Lar-Win, 1994	898 mm/yr	catchment water balance	Falerne catchment
Ni-Lar-Win, 1994	1483 mm/yr	catchment water balance	YenI catchment
Nizhizawa & Koike, 1992	1451 mm/yr	annual water budget	Amazon Basin
Odum et al., 1970b	1860-2154 mm/yr	n/a	Tabonuco forest at El Verde, in the Luquillo Experimental Forest
Oki *et al*., 1999	1023 mm/yr	annual water budget	Amazon Basin
Oliphant, *et al*., 2002	1600 MJ	n/a	midwestern deciduous hardwood forest; transition zone, mixed species, selectively logged, Morgan Monroe State Forest (MMSF), extensive secondary successional broadleaf forest, in the maple-beech to oak-hickory transition zone
Oyebande, 1988	945 mm/yr	n/a	Loweo Catchment in the Yangambi Forest Reserve in Zaire
Pavlov, 1976	200-240 mm/yr	n/a	boreal forest
Pearce & Rowe, 1979 Rowe, 1979	1100 mm/yr	n/a	experimental mixed forest for Maimai catchment, South Island, New Zealand
Pearce et al., 1976	1100 mm/yr	catchment water balance	mixed beech forest in Maimai (M7) catchment
Pearce et al., 1976	1100 mm/yr	catchment water balance	mixed beech forest in Maimai (M9) catchment
Pereira, 1964	1154 mm/yr	catchment water balance	bamboo forest in Kimakia catchment
Pike, 1964	814 mm/yr	catchment water balance	LilongI catchment
Pike, 1964	1107 mm/yr	catchment water balance	Luweya catchment
Pike, 1964	807 mm/yr	catchment water balance	Rivi Rivi catchment
Pilgrim et al., 1982	600 mm/yr	catchment water balance	native eucalypt forest at Lidsdale, Australia
Pinol et al., 1991	502 mm/yr	catchment water balance	forest in L'Avic catchment, Prades, northeast Spain
Pinol et al., 1991	515 mm/yr	catchment water balance	forest in La Teula catchment, Prades, northeast Spain
Poels, 1987	1630 mm/yr	catchment water balance for a 295 ha basin;	clearcutting just outside basin; leakage via earthen dam with sharp-rested weir quantified by that via sandy valley bottom assumed negligible, possibly overestimate (Bruijnzeel., 1990); Tonka, Surinam
Post & Jones, 2001	968, 981, 1007 mm/yr	catchment water balance	Andrews 2,8,9 long term control basins, in Andrews Experimental LTER
Post & Jones, 2001	954, 866, 916, 719, 834, 831, 528 mm/yr	catchment water balance	Coweeta 2, 14, 18, 27, 32, 34, 36 basins in Coweeta experimental forest
Post & Jones, 2001	497, 497, 525, 496, 530 mm/yr	catchment water balance	Hubbard Brook 1, 3, 6, 7, 8 basins in Hubbard Brook experimental forest
Post & Jones, 2001	1825, 1802, 1788 mm/yr	catchment water balance	Luquillo Bisley Catchment 1, 2, 3
Rao *et al*., 1996	4.5 mm/day	water balance	ECMWF assimilate data, Amazon basin

Rauner, 1966	400-450 mm/yr	it has been suggested [Zubenok, 1976, Rakhmanov, 1981, Gidromet, 1976, Fedorov, 1977] that Rauner overestimated forest ET by approximately 5 to 15%	calculated the evaporation from forests of the European former USSR and plotted isoline maps
Rauner, 1966	500 mm/yr	it has been suggested [Zubenok, 1976, Rakhmanov, 1981, Gidromet, 1976, Fedorov, 1977] that Rauner overestimated forest ET by approximately 5 to 15%	calculated the evaporation from forests of the European former USSR and plotted isoline maps
Rauner, 1966	575 mm/yr	it has been suggested [Zubenok, 1976, Rakhmanov, 1981, Gidromet, 1976, Fedorov, 1977] that Rauner overestimated forest ET by approximately 5 to 15%	calculated the evaporation from forests of the European former USSR and plotted isoline maps
Rauner, 1966	525-550 mm/yr	it has been suggested [Zubenok, 1976, Rakhmanov, 1981, Gidromet, 1976, Fedorov, 1977] that Rauner overestimated forest ET by approximately 5 to 15%	calculated the evaporation from forests of the European former USSR and plotted isoline maps
Rauner, 1966	576-600 mm/yr	it has been suggested [Zubenok, 1976, Rakhmanov, 1981, Gidromet, 1976, Fedorov, 1977] that Rauner overestimated forest ET by approximately 5 to 15%	calculated the evaporation from forests of the European former USSR and plotted isoline maps
Ribeiro & Villa Nova, 1979	1508 mm/yr	Thornthwaite and Mather's method	Ducke Forest Reserve, Amazonia
Rich et al., 1961	727 mm/yr	catchment water balance	conifer forest, North Fork, Workman experimental watershed
Rich et al., 1961	726 mm/yr	catchment water balance	conifer forest, South Fork, Workman experimental watershed
Rich, 1968	568 mm/yr	catchment water balance	Castle Creek catchment, conifer forest, Arizona
Richardson, 1982	2000 mm/yr	CWB	submontane forest on the leeward side of Jamaica (leaky catchment)
Roberts, 1998	517, 629, 832, 1089 mm/yr	empirical relations	lowland and upland coniferous forests
Roberts, 1998	384-445 mm/yr	empirical relations	lowland and upland coniferous forests
Roche, 1982	1528 mm/yr	catchment water balance for 840 ha basin	Gregoire 1, French Guyana
Roche, 1982	1437 mm/yr	catchment water balance for 1240 ha basin	Gregoire 2, French Guyana
Roche, 1982	1444 mm/yr	catchment water balance for 320 ha basin	Gregoire 3, French Guyana
Rockstrom *et al*., 1999	729 mm/yr (range 588-964)	4 literature sources	predominantly deciduous forest
Rockstrom *et al*., 1999	792 mm/yr (range 783-800)	2 literature forests	tropical / subtropical dry / deciduous / seasonal forest
Rockstrom *et al*., 1999	487 mm/yr	4 literature sources	predominantly coniferous forests
Rockstrom *et al*., 1999	401 mm/yr (range is from 380-420)	3 literature sources	taiga
Rockstrom *et al*., 1999	401 mm/yr (range is from 380-420)	3 literature sources	taiga
Rockstrom *et al*., 1999	0.442 m/yr	catchment water balance	90% of TET
Rockstrom *et al*., 1999	1245 mm/yr (range 880-1493 mm/yr)	3 literature sources	tropical / subtropical wet forest

continuation of Table E5. ET of forests

Rosenzweig, 1968	log 2.75 mm/yr	model (Thornthwaite)	climax beech-maple forest Toronto ON, Canada
Rosenzweig, 1968	log 2.92 mm/yr	model (Thornthwaite)	oak-hickory forest, Oak Ridge TN
Rosenzweig, 1968	log 2.69 mm/yr	model (Thornthwaite)	grey beech forest, Gt. Smky Mts TN
Rosenzweig, 1968	log 2.85 mm/yr	model (Thornthwaite)	deciduous cove forest, Gt. Smky Mts TN
Rosenzweig, 1968	log 3.12 mm/yr	model (Thornthwaite)	tropical forest ,Yangambi, Congo (Leopoldville
Rosenzweig, 1968	log 2.61, 2.64, 2.68 mm/yr	model (Thornthwaite)	fraser fir and spruce fir forest Gt. Smky Mts TN
Rosenzweig, 1968	log 2.82 mm/yr	model (Thornthwaite)	hemlock – mixed forest, Gt. Smky Mts TN
Rosenzweig, 1968	log 2.75 mm/yr	model (Thornthwaite)	hemlock – rhododendron forest, Gt. Smky Mts TN
Running *et al.*, 1989	40-60 cm/yr	simulation model (FOREST-BGC)	predominantly coniferous forests in western Montana, the part of the study area that was not heavily clearcut
Russell & Miller, 1990	1620 mm/yr	annual water budget	Amazon Basin
Schafer *et al.*, 2002	537.1, 575.0, 614.3 W/m^2	micrometeorological measurements, eddy covariance	Duke Forest, North Carolina
Schellekens et al., 2000	6.6-6 mm/day	micrometeorological measurements, Penman Monteith, catchment water balance	for lower tropical rainforest, below 600 m; a recent detailed measurement; 6.6 mm/d in 1996 and 6.0 mm/d in 1997; average ET for forest ; using combination of micrometeorological and hydrological methods
Scott & Lesch, 1997	1168 mm/yr	catchment water balance	Eucalyptus in Mokobulaan (A) catchment
Scott & Lesch, 1997	1122 mm/yr	catchment water balance	Eucalyptus in Mokobulaan (B) catchment
Sharma, 1984	923 (+/- 57) mm/yr	water balance method	Eucalypt forest in southwestern Australia
Sharpe, 1970	341 (44 SD) mm/yr	measured at site, Thornthwaite method	station C-1, Niwot Ridge, Front Range, Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Sharpe, 1970	330 (45 SD) mm/yr	measured at site, Thornthwaite method	Berthoud Pass, Front Range, Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Sharpe, 1970	321 (63 SD) mm/yr	measured at site, Thornthwaite method	Leadville, Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Sharpe, 1970	321 (46 SD) mm/yr	measured at site, Thornthwaite method	Climax, 2NW Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Sharpe, 1970	381 (29 SD) mm/yr	measured at site, Thornthwaite method	Lake Moraine, Pike's Peak Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Sharpe, 1970	369 (32 SD) mm/yr	measured at site, Thornthwaite method	Wolf Creek Pass 1 East, Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Sharpe, 1970	326 (34 SD) mm/yr	measured at site, Thornthwaite method	Summitville, Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest

continuation of Table E5. ET of forests

Sharpe, 1970	334 (51 SD) mm/yr	measured at site, Thornthwaite method	Wagon Wheel Gap Expt. Station, Colorado; assumed 100 mm of available soil moisture storage capacity; upper Montane forest
Sharpe, 1970	300 (50 SD) mm/yr	measured at site, Thornthwaite method	Wagon Wheel Gap Expt. Station, near Timberline, Colorado; assumed 100 mm of available soil moisture storage capacity; subalpine forest
Shuttleworth, 1988	1315 mm/yr	BREB; intensive field campaigns, combined Penman-Monteith-Rutter model using continuous above-canopy climatic data	Manaus rainforest; based on micrometeorology model coupling measurements of available net energy with continuous measurements of rainfall interception loss at Reserva Ducke near Barro Branco catchment
Shuttleworth, 1988	1274-1344 mm/yr	micrometeorological measurements, soil water balance	primary Amazonian rainforest near Manaus
Silbertein et al., 1999	1115 mm/yr	forests in Salmon catchment, within Collie River catchment, in southwest of Western Australia	
Steinhardt, 1979	980 mm/yr	energy balance	mossy lower montane rain forest (transition to cloud forest), San Eusebio, Venezuela
Stoneman, 1993	931 mm/yr		jarrah forest, Western Australia
Sumner, 2001	993 mm/yr	energy budget variation of eddy correlation	Tiger Bay watershed Volusia County, Florida, pine flatwood tree plantation
Sun *et al*., 1998	1002.7 mm/yr	FLATWOODS model	"control" sites in North central Florida: Gator National forest and Bradford forest; two sites simulated for a dry, normal, wet year
Sun *et al*., 2002	779 mm/yr	model	mature deciduous oak hardwoods in mountainous North Carolina
Tajchman *et al*., 1997	817 mm/yr	water balance	oaks and maple in Appalachians
Tattari & Ikonen, 1997	600, 620, 605 mm/yr	ASTIM model	Pine and spruce forests on moraine, and pine swamps
Thornton *et al*., 2002 Law *et al*., 2002	357, 339 mm/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	Howland forest, ME, select cut 1910
Thornton *et al*., 2002; Law *et al*., 2002	521, 444 mm/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	Metolius, OR; fire disturbance in 1750, 1850, 1950
Thornton *et al*., 2002; Law *et al*., 2002	640, 537 mm/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	Nitwot ridge CO (harvested 1905, assume returned to equilibrium after 95 years)
Thornton *et al*., 2002; Law *et al*., 2002	542, 443 mm/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	Wind river Washington State
Tiktak & Bouten, 1994	712 mm/yr	model `SWIF'	Douglas Fir Stand in the Netherlands
TVA, 1961	720 mm/yr	Catchment water balance	Douglas Fir forests in White Hollow Catchment, TN
Unland *et al*., 1998	1.697 m/yr	micrometeorological measurements, soil water balance	cottonwood in riparian area of Santa Cruz River in southern Arizona
Vertessy & Bessard, 1999	678 mm/yr	n/a	forest in New South Wales
Vertessy *et al*., 1996	635 mm/yr	ecohydrological water balance model (Topog-IRM)	mountain ash Picaninny (0.53 km^2) forest catchment, Victoria, Australia; old growth mountain ash forest (about 200 years old); doesn't include interception losses
Vertessy *et al*., 2001	911 mm/yr	sap flow, lysimeter	240 yr old Ash / Eucalypt forest in Victoria, Australia
Vesala & Launiainen, 2004	329 mm/yr	Eddy covariance	coniferous forest at Hyytiala site

continuation of Table E5. ET of forests

Villa Nova *et al*., 1976	1168 mm/yr	micrometeorological measurements	Amazon basin
Villa Nova *et al*., 1976	1080 mm/yr	annual water budget	Amazon basin
Vorosmarty & Wilmott, 1999	1221 mm/yr	WBM/WTM computed water balance	Amazon basin, upriver of Obidos
Vorosmarty *et al*., 1989	1250 mm/yr	annual water budget	Amazon basin
Vorosmarty *et al*., 1996	3.3 mm/d	model (Thornthwaite)	Amazon basin
Vourlitis *et al*., 2002	6.91(+/- 0.80) MJ/m^2/day	eddy covariance	extensive mature, intact forest, north of Sinop, Mato Grosso, Brazil
Walter & Hedin, 2002	430 mm/yr	watershed mass balance	remote unpolluted Chilean old growth forests
Waterloo, 1994	1512 mm/yr	n/a	mature pine stand in Fiji
White *et al*., 1999	57.5 (SD 0.9) cm/yr	ecosystem model (BIOME-BGC)	Burlington Vt. site in deciduous broadleaf forest
White *et al*., 1999	49.9 (SD 0.6) cm/yr	ecosystem model (BIOME-BGC)	Portland Me. site in deciduous broadleaf forest
White *et al*., 1999	56.7 (SD 0.9) cm/yr	ecosystem model (BIOME-BGC)	Albany, NY site in deciduous broadleaf forest
White *et al*., 1999	54.6 (SD 0.9) cm/yr	ecosystem model (BIOME-BGC)	Blue Hill, Mass. site in deciduous broadleaf forest
White *et al*., 1999	55.9 (SD 0.9) cm/yr	ecosystem model (BIOME-BGC)	Ann Arbor, Mich. site in deciduous broadleaf forest
White *et al*., 1999	62.1 (SD 0.9) cm/yr	ecosystem model (BIOME-BGC)	Wooster Ohio site in deciduous broadleaf forest
White *et al*., 1999	62.7 (SD 1.0) cm/yr	ecosystem model (BIOME-BGC)	Monmouth, Ill. site in deciduous broadleaf forest
White *et al*., 1999	59.8 (SD 1.1) cm/yr	ecosystem model (BIOME-BGC)	New Brunswick, NJ site in deciduous broadleaf forest
White *et al*., 1999	63.1 (SD 1.1) cm/yr	ecosystem model (BIOME-BGC)	Washington, Ind. site in deciduous broadleaf forest
White *et al*., 1999	69.6 (SD 1.0) cm/yr	ecosystem model (BIOME-BGC)	Rogersville, Tenn. site in deciduous broadleaf forest
White *et al*., 1999	69.7 (SD 0.8) cm/yr	ecosystem model (BIOME-BGC)	Monroe N.C. site in deciduous broadleaf forest
White *et al*., 1999	66.0 (SD 0.6) cm/yr	ecosystem model (BIOME-BGC)	Charleston, S.C. site in deciduous broadleaf forest
White et al., 2002	595 mm	Catchment water balance	eucalyptus tree belts in pasture area
Williams *et al*., 1998	818 mm/yr	eddy covariance, soil plant atmosphere model	virgin terra firme forest in Reserva Biologica do Cuieiras
Williams et al., 2001	436 +/- 65, 400 +/- 60 mm/yr	Metolius ponderosa pine site, eastern Cascades; mixed age	
Wilson & Baldocchi, 2000	567.2 mm/yr	eddy covariance, micrometeorological measurements	estimated evaporation (sum of measured evaporation and the estimated evaporation when data was missing. For NA temperate deciduous forest
Williams *et al*., 2001	436 +/- 65 mm/yr, 400 +/- 60 mm/yr	eddy covariance, model	metolius ponderosa pine site, eastern Cascades; mixed age

Wilson *et al*., 2001	645 (+/- 20) mm/yr	catchment water balance	uneven-aged mixed deciduous forest in southeastern USA
Wilson *et al*., 2001	571 (+/- 16) mm/yr	eddy covariance	uneven-aged mixed deciduous forest in southeastern USA
Zeng, 1999	1879 mm/yr	catchment water balance	annual water budget for Amazon basin
Zhang & Wu, 2002	250,200,125-450,360,225 cm/yr	statistical thermodynamic model	tropical rainforest; following Wittaker, 1975
Zierl, 2001	617 mm/yr	bucket hydrological model (WAWAHAMO)	conifer and Deciduous trees in Switzerland

Table E6. Annual evapotranspiration of natural grassland (ET_{gs})

Source	ET	Method	Description
Addison, 1977	75 mm/yr		arctic semi-desert dominated by cushion plants, lichens and mosses, total plant cover 70-90 %
ADWR, 1991	954 mm/yr	Blaney-Criddle	cienega / dense grass in riparian area of the San Pedro River Basin, Sierra Vista sub watershed
ADWR, 1991	486, 756 mm/yr	Blaney-Criddle	dense and medium-dense mesquite, Sierra Vista sub watershed of the San Pedro River Basin, Arizona
Arkley, 1967	7.7 in/yr	model (Thornthwaite)	assumed soil moisture capacity of 6 inches
Bailly *et al*., 1974	1425 mm/yr	soil water balance	Manankazo, Madagascar, pinus patula plantation, 4-10 yrs
Balek & Perry, 1973	500 mm/yr	n/a	dambo grassland Luano catchment, Zambia
Balek & Perry, 1973	1000-1350	n/a	Brachystegia woodland, Luano catchment, Zambia
Bastiaanssen & Bandara, 2001	1,232 mm/yr	remote sensing	scrubland in Kirindi Oya, Sri Lanka
Bellot *et al*., 1999	265.6 mm/yr	hydrological model, negative exponential approach	semi-arid Mediterranean area of Ventos (Alicante, Spain)
Bellot *et al*., 1999	325.1 mm/yr	hydrological model, negative exponential approach	semi-arid Mediterranean area of Ventos (Alicante, Spain)
Berger, 2001	4.07 - 5.73 ft/yr	Bowen-Ratio Energy-Balance, eddy correlation	meadow and grassland in Ruby Lake National Wildlife Refuge Area, Ruby Valley, northeastern Nevada
Berger, 2001	11.96- 15.89 in/yr		desert-shrub upland and moderate cover of mixed phreatophytes in Ruby Lake National Wildlife Refuge Area, Ruby Valley, Northeastern Nevada
Bernard, 1948	95-100 cm /yr	direct measurements	savannah country in Belgian Congo, central basin
Bidlake *et al*., 1996	1010 mm/yr	Bowen-Ratio Energy-Balance	dry prairie vegetation in west-central Florida
Bosch & Hewlett, 1982	800 mm/yr	catchment water balance	Fynbos in Biesievlei catchment
Bosch & Hewlett, 1982	800 mm/yr	catchment water balance	Fynbos in Bosboukloof catchment
Bosch & Hewlett, 1982	837 mm/yr	catchment water balance	Fynbos in Lambrerchtsbos (A) catchment
Bosch & Hewlett, 1982	991 mm/yr	catchment water balance	Fynbos in Lambrerchtsbos (B) catchment
Bosch & Hewlett, 1982	709 mm/yr	catchment water balance	Fynbos in Tierkloof catchment
Brye et al., 2000	515, 486 mm/yr	soil water balance	for prairie plot, restored from an agricultural field in 1976, and burned every three years, except no burning for 5 years before the study
Calder, 1982	799 mm/yr		Wye catchment

continuation of Table E6. ET of grassland

Caldwell *et al*., 1977	225 mm/yr		shrub in cool grassland in Curlew Valley
Campbell & Murray, 1990	622 mm/yr		grassland in Otago, New Zealand
Campbell & Murray, 1990	536 mm/yr	lysimeter	narrow-leaved snow tussock, in a broad tussock covered ridge 570 m above sea level, in the upper Waipori catchment in eastern Otago, NZ.
Carlson *et al*., 1990	654 mm/yr	lysimeter	shrub and shrub with Mesquite; eastern ridge of Rolling Plains resource region, within a 16 ha livestock enclosure, TX
Chen *et al*., 1997	526 mm/yr	meteorological observations	short grass vegetation, Cabauw, Netherlands
Choudhury *et al*., 1998	894-1090 mm/yr	biophysical process-based model with satellite & ancillary data	range for annual average values for 3 regions: N. Africa, S. Africa and S. America
Choudhury *et al*., 1998	220 mm/yr	biophysical process-based model with satellite & ancillary data	tundra
Choudhury *et al*., 1998	171 mm/yr	biophysical process-based model with satellite & ancillary data	tundra
Choudhury *et al*., 1998	262 mm/yr	biophysical process-based model with satellite & ancillary data	tundra
Choudhury *et al*., 1998	193 mm/yr	biophysical process-based model with satellite & ancillary data	tundra
Choudhury *et al*., 1998	1000 mm/yr	biophysical process-based model with satellite & ancillary data	savannah
Choudhury *et al*., 1998	894 mm/yr	biophysical process-based model with satellite & ancillary data	savannah
Choudhury *et al*., 1998	900 mm/yr	biophysical process-based model with satellite & ancillary data	savannah
Christen & Vogt, 2004	700 mm/yr	lysimeter	for grassland near Basel, Switzerland
Cook *et al*., 1998	1110 mm/yr	eddy covariance / energy balance	Howard River, NT, Australia; assuming wet season evaporation in this region scales with radiation, and use monthly global irradiation values to constrain annual ET estimate; open eucalypt woodland
Dirnbock & Grabner, 2000	180-270 mm/yr	energy balance, model	Carex firma and Sesleria-Carex sempervirens grassland
Dunin *et al*., 1978	11 mm/yr	resistance model	Themeda Grassland in the Southern Tablelands region of New South Wales, Australia
Dunn & Mackay, 1995	411-473 (SD 25.5) mm/yr	model, based on Penman-Monteith with Rutter interception	bracken (heaths and moorlands) in Tyne Basin in North East England
Dye, 1996	548 mm/yr	catchment water balance	scrub forest in Westfalia catchment
Everson, 2001	695.5 mm/yr	Bowen Ratio Energy Balance, Penman Monteith, Equilibrium equation	Cathedral Peak Forestry Research Station, northern Natal Drakensberg Park, South Africa, received biennial spring burning treatment
Federov, 1977	469 mm/yr (SD 28)	micrometeorological measurements, energy balance, lysimeters	grassland at Usadievskiy Valdai station, Russia
Flerchinger *et al*., 1996 Flerchinger *et al*., 2000	376 (+/- 3 mm), 338 (+/- 51 mm), 360 mm	Simultaneous Heat and Water Model (SHAW), detailed physical process model applied to 2 years of data	southwestern Idaho, low sagebrush, using SHAW model and meteorological measurements
Flerchinger *et al*., 1996, Flerchinger *et al*., 2000	569 (+/- 3 mm), 505 (+/- 51 mm), 492 mm	Simultaneous Heat and Water Model (SHAW), detailed physical process model applied to 2 years of data	southwestern Idaho, mountain big sagebrush, using SHAW model and meteorological measurements
Franco-Vizcaino *et al*., 2002	446 +/- 122 mm/yr	soil water balance, neutron prove, mini-lysimeters	wet meadow site

continuation of Table E6. ET of grassland

Frank & Inouye, 1994	413 mm/yr	model (Thornthwaite)	shortgrass prairie, 13 sites: 1) El Obeid Sudan, 2) Kimberley South Africa, 3) Mopti Mali, 4) Nairobi Kenya, 5) Pietersburg South Africa, 6) Oktiabrskii, Ukraine, 7) Orenburg, Russia, 8) Rostov-na-donu, Russia, 9) Cheynne, WY, 10) Havre, MT, 11) Lubbock TX , 12) Hobbs NM, 13) Rocky Ford CO
Frank & Inouye, 1994	571 mm/yr	model (Thornthwaite)	tallgrass prairie, 5 sites: 1) Clinton OK, 2) Crete NB, 3) Great Bend KS, 4) Lamberton MN, 5) Waterton SD
Frank & Inouye, 1994	202 mm/yr	model (Thornthwaite)	10 tundra sites: 1) Baker Lake Canada, 2) Hall Beach Canada, 3) Mould Bay Canada, 4) Resolute Canada, 5) Sachs Harbour, Canada, 6) Barrow, AK, 7) Bethel AK, 8) King Salmon AK, 9) Kotzebue AK, 10) Nome AK
Frank & Inouye, 1994	894 mm/yr	model (Thornthwaite)	savannah for four sites, one in Songea Tanzania, Africa, one in Brasilia, Brazil, one in Cuiba Brazil, on in San Fernando, Venezuela
Goetz & Shelton, 1990	33.9 in/yr	Bowen-ratio Energy Balance, micrometeorological measurements, and portable field chamber	clover and weeds in Albuquerque, NM
Gray, *et al*., 1998	1360 mm/yr	n/a	Konza Prairie, eastern Kansas; unplowed
Gutowski *et al*., 2002	1.84 mm/day	model	coupled Land-Atmosphere Simulation Program at the FIFE Konza Prairie site; C4 tallgrass prairie
Hall & Harding, 1993	484, 460, 398, 395 mm/yr	model; M(AZ11), Penman-Monteith	two catchments in the Balquidder watershed
Hargreaves & Samani, 1986	1927 mm/yr	n/a	for grassland in Mali, 1960-1985
Hibbert, 1971	418 mm/yr	catchment water balance	chaparral in Natural Drainage (A) catchment
Hibbert, 1971	645 mm/yr	catchment water balance	chaparral in Three Bar (F) catchment
Hibbert, 1971	515 mm/yr	catchment water balance	chaparral in White Spar catchment
Hibbert, 1971	631 mm/yr	catchment water balance	chaparral in Three Bar (D) catchment
Hibbert, 1971; Hibbert, 1979	409 mm/yr	catchment water balance	chaparral in Natural Drainage (C) catchment
Hinzman, 1990 Kane *et al*., 1990	153, 130, 219, 240 mm/yr	water balance method; pan evaporation, energy balance and Priestley Taylor	2.2 km^2 Imnavait watershed, Alaska; tussock sedges and mosses, lichens and shrubs (willows, alder and dwarf birch)
Hoffman & Jackson, 2000	987 mm/yr	simulation with land surface model	cerrado, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	1023 mm/yr	simulation with land surface model	llanos, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	823 mm/yr	simulation with land surface model	northern Africa, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	804 mm/yr	simulation with land surface model	southern Africa, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	719 mm/yr	simulation with land surface model	Australia, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	1142 mm/yr	simulation with land surface model	llanos, from GCM model
Hoffman & Jackson, 2000	896 mm/yr	simulation with land surface model	southern Africa, from GCM model
Hoffman & Jackson, 2000	894 mm/yr	simulation with land surface model	northern Africa, from GCM model
Hoffman & Jackson, 2000	1080 mm/yr	simulation with land surface model	cerrado; from GCM model
Hoffman & Jackson, 2000	789 mm/yr	simulation with land surface model	Australia, from GCM model
Hutley *et al*., 2000	958 mm/yr	eddy covariance, heat pulse and open top chambers	eucalypt open-forest in Howard Springs, Northern Territory, Australia
Jackson *et al*., 1998	230-358 mm/yr	simulated with water balance model based on 10 year weather data	annual C3 grasslands at Jasper Ridge Biological Preserve in Palo Alto, California

Johnston, 1970	15.27 in/yr	soil water balance	plot: 49% veg, 21% litter, 30% bare, located near head of Parrish Canyon on the Davis County Experimental Watershed near Bountiful, Utah, elevation 8400 feet asl
Kane, et al. 1990	153, 130, 219, 240 mm/yr	site water balance, pan, energy balance, Priestley-Taylor	no ET estimate for winter; Arctic North slope of Alaska. vegetation is primarily water tolerant plants such as sedge tussocks and mosses, but they are accompanied by lichens and shrubs such as willow, alder and dwarf birch; Imnavait Creek, 2.2 km2 watershed
Kergoat *et al*., 2002	883, 933, 891, 956, 923 mm/yr	global vegetation model	grass / crops using CLIM, RAD, STOM, FERT, and MAX simulations
Kergoat *et al*., 2002	97, 121, 106, 141, 126 mm/yr	global vegetation model	tundra using CLIM, RAD, STOM, FERT, and MAX simulations
Kergoat *et al*., 2002	237, 246, 253, 246, 253 mm/yr	global vegetation model	Mediterranean vegetation / shrublands using CLIM, RAD, STOM, FERT, and MAX simulations
Laczniak *et al*., 1999	35.4 in/yr	micrometeorological measurements, Bowen-Ratio Energy-Balance	has a high concentration of springs; mixed grassland and shrubland vegetation in the North-Central Mojave Desert
Lane *et al*., 1984	158 mm (SD 52 mm)/yr	continuous simulation model, micrometeorological measurements	perennial vegetation in the northern Mojave Desert
Lewis, 1968	378 mm/yr	water balance	grassland in Sierra Nevada foothills of California
Lewis, 1968	510 mm/yr	water balance	oak woodland in Sierra Nevada foothills of California
L'vovitch, 1979	360.0-361.0 mm/yr	n/a	mowed virgin steppe, and for virgin steppe not mowed (observations during a 3-year period)
L'vovitch, 1979	450 mm/yr	n/a	temperate steppes
L'vovitch, 1979	280 mm/yr	n/a	subtropical and tropical desertic savannah
L'vovitch, 1979	870 mm/yr	n/a	subtropical and tropical dry savannah
L'vovitch, 1979	1200 mm/yr	n/a	subtropical and tropical wet savannah
L'vovitch, 1979	530 mm/yr	n/a	temperate wooded steppes and prairies
Mahmood & Hubbard, 2002	694 mm/yr	soil water balance model	pre-agricultural natural grass vegetation in tall grass - short grass transition in Nebraska, USA
Major, 1963	101 mm/yr	Thornthwaite, soil water balance	Ulan Bator, Mongolia, in the cold desert
Major, 1963	104 mm/yr	Thornthwaite, soil water balance	Barrow Alaska, USA, coastal tundra
Major, 1963	123 mm/yr	Thornthwaite, soil water balance	Yeringon, Nevada, USA, Great Basin shrub steppe
Major, 1963	250 mm/yr	Thornthwaite, soil water balance	Ellery Lake, California, USA at timberline (3230 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	226 mm/yr	Thornthwaite, soil water balance	Ellery Lake, California, USA at Dana Plateau (3770 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	180 mm/yr	Thornthwaite, soil water balance	White Mountains, California, USA (3800 m elevation); assuming 100 mm available soil moisture storage capacity
Major, 1963	273 mm/yr	Thornthwaite, soil water balance	xeric scrublands near Alice Springs, Australia
Major, 1963	414 mm/yr	Thornthwaite, soil water balance	Cloverdale California, chaparral and woodland
Malaisse, 1978	1050 mm/yr	n/a	Miombo woodland in Lubumbashi
Mather & Yoshioka, 1966	380 mm/yr	n/a	along timberline in Canada
Maykut & Church, 1973	72 mm/yr	water balance	tundra in Point Barrow

continuation of Table E6. ET of grassland

Miller, 1983	175 mm/yr	n/a	low arctic shrub
Miller, 1983	200 mm/yr	n/a	tall arctic shrubland
Miyazaki et al., 2004	117, 103 mm/yr	badpass-covariance method, using gap-filled data	on grass field in old airport at Avraikheer; winter ET assumed to be 0
Mocko & Sud, 1998	78.2, 75.1, 47.1, 60.3 W/m2	by energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	for globe, Wooded C4 grassland
Mocko & Sud, 1998	19.1, 19, 7.7, 17.7, 17.4, 14.2, 10.5, 7.3 W/m2	by energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	for globe, Broadleaf shrubs with bare soil, Broadleaf shrubs with groundcover
Mocko & Sud, 1998	39.7, 38.4, 22.2, 33.5 W/m2	by energy balance methods (Penman, Priestley-Taylor, Mintz-Thornthwaite) and by SSiB (simplified simple biosphere model)	for globe, grassland
Mo *et al*., 2004	635 mm/yr	process-based distributed model	grass, Lushi basin, China
Mo *et al*., 2004	640 mm/yr	process-based distributed model	dwarf shrublands, Lushi basin, China
Nichols, 2000	0.577 feet, 0.690 feet/yr	Bowen Ratio Energy Balance	barren land, shrubs and saltgrass, 12 Great Basin study sites, Nevada, USA
Ohmura, 1982	140 mm/yr	aerodynamic Methods, snow lysimeter, Bowen Ratio Energy Balance	arctic tundra on Axel Heiberg Island
Parton, Lauenroth & Smith, 1981	33.8 cm/yr	weighing lysimeter	Pawnee site in northeastern Colorado; shortgrass steppe
Petrone *et al*., 2000	168 mm/yr	Bowen-Ratio Energy Balance, eddy correlation using a vertical propeller anemometer	western subarctic dry site on tundra plateau 56 km northeast of Inuvik, NWT, Canada; assume no ET during winter months in subarctic
Poole *et al*., 1981	530 mm/yr	n/a	matorral in Funda Santa
Poole *et al*., 1981	395 mm/yr	n/a	chemise Chaparral, Echo Valley CA
Poole *et al*., 1981	475 mm/yr	n/a	mixed Chaparral, Echo Valley CA
Raymond & Rezin, 1989	2.36 feet/yr	remote sensing, water use rates	phreatophytes in southern Arizona
Riou, 1984	1070 mm/yr	n/a	Brazzaville, Congo, paspalum grass
Roberts, 1998	377-482 mm/yr	empirical relations	dry moorland
Rockstrom *et al*., 1999	410 mm/yr (range of 130-633 mm/yr)	compilation of literature	mostly temperate cool grassland
Rockstrom *et al*., 1999	655 mm/yr (range of 430-951 mm/yr)	compilation of literature	temperate mountainous grassland
Rockstrom *et al*., 1999	599 mm/yr (range of 403-862 mm/yr)	compilation of literature	mostly tropical warm and hot grassland
Rockstrom *et al*., 1999	600 mm/yr (range of 402-798 mm/yr)	compilation of literature	tropical mountainous grassland
Rockstrom *et al*., 1999	270 mm/yr (range of 225-315 mm/yr)	compilation of literature	tropical dry shrubland
Rockstrom *et al*., 1999	882 mm/yr (range of 870-894 mm/yr)	compilation of literature	savannah / woodland, dry
Rockstrom *et al*., 1999	1267 mm/yr (range of 1100-1500 mm/yr)	compilation of literature	savannah/woodland, wet
Rockstrom *et al*., 1999	416 mm/yr (range of 300-530 mm/yr)	compilation of literature	woodland/ woody savannah
Rockstrom *et al*., 1999	270 mm/yr (range of 225-315 mm/yr)	compilation of literature	tropical dry shrubland

continuation of Table E6. ET of grassland

Roose, 1979 Hutley *et al*., 2000	1064 mm/yr	water balance	savannah, Ivory Coast
Rosenzweig, 1968	log 2.79 mm/yr	model (Thornthwaite)	tall grass prairie Norman OK, USA, Penfound, 1964
Rosenzweig, 1968	log 2.37 mm/yr	model (Thornthwaite)	alpine moist tundra Mt. Washington NH, USA
Rosenzweig, 1968	log 2.30 mm/yr	model (Thornthwaite)	arctic moist tundra Cape Thompson AK, USA
Rosenzweig, 1968	log 2.25 mm/yr	model (Thornthwaite)	cheatgrass Hanford Reservation, WA
Rosenzweig, 1968	log 2.58 mm/yr	model (Thornthwaite)	heath bald (leiophyllum) Great Smky Mtns TN, USA
Rosenzweig, 1968	log 2.72, 2.69 mm/yr	model (Thornthwaite)	mixed heath, Great Smky Mtns TN, USA
Rowe, 1963	584 mm/yr	catchment water balance	chaparral in Monroe Canyon catchment
San Jose & Montes, 1992, 1995	783 mm/yr	water balance	Orinoco Savanna, Venezuela
Scholes & Walker, 1993	445-717 mm/yr	simulation model, climatological data, soil water balance	water budget for broad-leafed savannah at Nylsvley
Scott *et al*., 2000	272 mm/yr	Bowen-Ratio Energy Balance, micrometeorological measurements, eddy covariance	sacaton grass site in the semiarid riparian area of San Pedro River in southeastern Arizona
Scott *et al*., 2000	375 mm/yr	Bowen-Ratio Energy Balance, micrometeorological measurements	mesquite site in the semiarid riparian area of San Pedro River in southeastern Arizona
Sharpe, 1970	343.54 (1910), 384 mm/yr (avg for 1911-1920)	measured at site, and model (Thornthwaite)	Sill Mine, Colorado, 3510 metres at lower end of plateau, 1/2 mile from foot of high mountains, and just at the edge of timberline, in Clear Creek County, Colorado. For plot, PE is counted as zero when mean temperature is below 0oC. For catchment estimate, assumed 100 mm of available soil moisture storage capacity, and includes snow evaporation estimate of 50 mm.
Sharpe, 1970	268 (SD 26) mm/yr	measured at site, and model (Thornthwaite)	station D-1, Nitwot Ridge, Front Range, Colorado; assumed 100 mm of available soil moisture storage capacity; alpine tundra
Sharpe, 1970	275 (SD 45) mm/yr	measured at site, and model (Thornthwaite)	Corona Pass, Front Range, Colorado; assumed 100 mm of available soil moisture storage capacity; alpine tundra
Sharpe, 1970	335 (SD 30) mm/yr	measured at site, and model (Thornthwaite)	Pike's Peak Timberline, Colorado; assumed 100 mm of available soil moisture storage capacity; timberline
Sharpe, 1970	317 (SD 41) mm/yr	measured at site, and model (Thornthwaite)	average alpine timberline climate based on six high elevation weather station-pairs in Colorado USA
Sims, Singh & Laurenroth, 1978	158-729 mm/yr	n/a	10 US Grasslands
Smith-Carrington, 1983	640 mm/yr	n/a	Bua catchment, dambo grassland
Smith-Carrington, 1983	700-750 mm/yr	n/a	Bua catchment, woodland interfleuve and fallow interfleuve, Malawi
Stuart *et al*., 1982	125 mm/yr	n/a	tussock tundra, common in AK and former USSR, infrequent in Canada
Sumner, 1996	680 mm/yr	eddy correlation, Penman Monteith	several methods, eddy correlation, penman Monteith, for grassland in central Florida, that was previously forested
Tattari & Ikonen, 1997	500 mm/yr	ASTIM model	fields and treeless areas on moraine, Hietajärvi, Finland
Thompson *et al*., 1981	430 mm/yr	n/a	grassland

continuation of Table E6. ET of grassland

Tomlinson, 1996	260 mm/yr	Bowen-Ratio Energy Balance, lysimeter, Penman-Monteith	full canopy grassland site (Snively Basin), Spokane and Yakima County, Washington State, USA
Tomlinson, 1996	233 mm/yr	Bowen-Ratio Energy Balance, lysimeter, Penman-Monteith	full canopy grassland site (Turnbull Meadow), Spokane and Yakima County, Washington State, USA
Tomlinson, 1996	234 mm/yr	Bowen-Ratio Energy Balance, lysimeter, Penman-Monteith	sagebrush grassland (Black Rock Valley site) , Spokane and Yakima County, Washington State, USA
Tomlinson, 1997	417 mm/yr	Bowen-Ratio Energy Balance, micrometeorological measurements	grassland, Bird Canyon, Washington State
Tomlinson, 1997	352, 372, 199, 469 mm/yr	Bowen-ratio Energy Balance, micrometeorological measurements, Penman Monteith, lysimeter	sagebrush, Black Rock Valley, Washington State
Tuvedendorzh & Myagmarzhav, 1985	190 mm/yr	Budyko's method	at Avraikheer
Unland *et al*., 1998	0.848 m/yr	Bowen-ratio Energy Balance, micrometeorological measurements	medium / high density vegetation of medium height (primarily facultative phreatophytes, especially mesquite bosque) in Santa Cruz River in southern Arizona
Vardavas, 1988	935 mm/yr	Priestly & Taylor, 1972	Magela Creek NT, Australia
Vertessy & Bessard, 1999	0.603 m/yr	n/a	grassland in New South Wales, Australia
Vertessy & Bessard, 1999	0.666 m/yr	n/a	woodland in New South Wales, Australia
Wever *et al*., 2002	215, 250, 265 mm/yr	eddy covariance, energy balance, Priestley Taylor	three grassland plots in southern Alberta; for northern temperate grassland; has not been grazed for over 20 years
Wright & Harding 1993	395-397 mm/yr	weighting lysimeter	Balquidder catchments in Wales, natural grassland, assuming minimal ET during snow season
Zakia, 1987	480 mm/yr	soil water balance	Minas Gerais, Brazil, grassland
Zhang *et al*., 1999	607 mm/yr	n/a	grasslands in Australia

Table E7. Annual evapotranspiration of grazing areas (ET_{gz})

Source	ET	Method	Description
Allen, 2000	870-940 mm/yr	using FAO56-PM equation and the 1985 Hargreaves equation	pasture in Gediz River, Turkey
Beljaars & Bosveld, 1997	523 mm/yr	micrometeorological measurements, tower	grass plot at Cabauw, Netherlands
Ben Wu et al., 2001	482.7 mm/yr	water balance	originally grassland, after grazing now is covered with woody vegetation: Ashe, redberry juniper, live oak, vasey shin oak, and herbaceous plants; · Cusenbary Draw Basin 209 km2,
Bethune & Wang, 2004	1230 mm/yr	lysimeter, model	irrigated pasture
Billesbach *et al*., 2002	550-680 mm/yr	Bowen Ratio - Energy Balance, micrometeorological measurements	temperate grasslands, savannas, and shrublands; range for dry valley (550 mm/yr) to wet meadow (680 mm/yr), for Nebraska Sand Hills; free-range grazing.
Calder, 2003	460, 486 mm/yr	HYLUC model	Greenwood Community Forest, grassland in sandy & loam soil
Choudhury & DiGirolamo, 1998(Choudhury and DiGirolamo 1998); Delfs, 1967	520 mm/yr	n/a	Harz Mountain
Clarke & Newson, 1978	421 mm/yr	water budget	Wye catchment in England, rough hill pasture

continuation of Table E7. ET of grazing land

Clifton & Taylor, 1995	395, 435, 525 mm/yr	n/a	annual and perennial pastures with medium cutting height
Cox & Pitman, 2002	752, 755, 826, 800, 785, 872, 878, 877, 870 mm/yr	water balance	different pasture and slope treatments
Dirnbock & Grabner, 2000	180-270 mm/yr	compilation of literature, modelling according to Turc-Wendling, an energy balance model	alpine pastures in Austrian alps
Dunin, 1965	440 mm/yr	catchment water balance	pasture in Parwan Creek, Australia
Dunn & Mackay, 1995	475 (SD 26.4) mm/yr	model based on Penman-Monteith with Rutter interception	pasture, rough grazing and grassland in the Tyne Basin in northeast England
Greenwood *et al*., 1985	390 mm/yr	ventilated chamber technique	pasture in North Bannister, Western Australia
Harr & Price, 1972	21-25 cm/yr	soil water balance	two greasewood-cheatgrass communities in south central Washington; heavily grazed prior to 1943, grazed intermittently from 1943-1960, and ungrazed since 1960; study area located near Rattlesnake Spring
Hibbert, 1971	510 mm/yr	catchment water balance	pasture in Three Bar (B) catchment
Hibbert, 1971	456 mm/yr	catchment water balance	pasture in Three Bar (C) catchment
Hicks et al., 2001	1027 mm/yr	micrometeorological measurements	Kaitaia Airfield meteorological site, from meteorological data collected
Hodnett et al., 1995	1.2 mm/day	soil water balance	pasture
Hoffman & Jackson, 2000	987 mm/yr	simulated with NCAR CCM3 general circulation model	for Cerrado, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	1023 mm/yr	simulated with NCAR CCM3 general circulation model	for Llanos, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	823 mm/yr	simulated with NCAR CCM3 general circulation model	for Northern Africa, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	804 mm/yr	simulated with NCAR CCM3 general circulation model	for Southern Africa, converted savannah to grassland, using GCM
Hoffman & Jackson, 2000	719 mm/yr	simulated with NCAR CCM3 general circulation model	for Australia, converted savannah to grassland, using GCM
Hoover, 1944	878 mm/yr	catchment water balance	pasture in Coweeta (17) catchment, NC
Hoyt & Troxell, 1934	477 mm/yr	catchment water balance	pasture in San Gabriel catchment
Hudson & Gilman, 1993	471 mm/yr	catchment water balance	sheep pasture in grassland Wye catchment, Plynlimon Mid Wales
Jipp *et al*., 1998	3.76 mm/day	micrometeorological measurements, soil water balance	pasture in a cattle ranch 6 km north of Paragominas in northern Brazilian state of Para; pastures originally cleared in the 1960s; invasive weedy vegetation is controlled with manual clearing and burning
Joffre & Rambal, 1993	400-590	soil water balance, Penman Monteith	Dehesa ecosystems savanna, grassland
Jolly et al., 1997	589 mm/yr	catchment water balance	pasture in Border catchment in Murray-Darling basin, Australia
Jolly et al., 1997	703 mm/yr	catchment water balance	pasture in Dumarasq catchment in Murray-Darling basin, Australia
Jolly et al., 1997	697 mm/yr	catchment water balance	pasture in Gwyder 1 catchment in Murray-Darling basin, Australia
Jolly et al., 1997	669 mm/yr	catchment water balance	pasture in Gwyder 2 catchment in Murray-Darling basin, Australia
Jolly et al., 1997	628 mm/yr	catchment water balance	pasture in Jugiong Creek catchment in Murray-Darling basin, Australia
Jolly et al., 1997	667 mm/yr	catchment water balance	pasture in Mehi catchment in Murray-Darling basin, Australia

continuation of Table E7. ET of grazing land

Jolly et al., 1997	585 mm/yr	catchment water balance	pasture in Wallurnburrawang Creek catchment in Murray-Darling basin, Australia
Leopoldo *et al*., 1993	2.1-3.8 mm/day	n/a	pasture in ABRACOS project near Manaus
Leppanen, 1980	377 mm/yr	Bowen Ratio-Energy Balance	flood plain that had been cleared of all tall vegetation by chaining, raking and burning about 6 months before measurements began; groundcover is sparse volunteer Bermuda grass and scattered seep willow; Gila River Valley, AZ; 1971-1972
Leppanen, 1981	989 mm/yr	Bowen Ratio-Energy Balance	planted forage grass; original cover of halophytic vegetation, consisting largely of seepweed, and iodine bush, and salt cedar; Gila River Valley, AZ; 1969-1970
Lewis *et al*., 2000	368 mm/yr (SD 89)	catchment water balance	partially harvested and grazed oak forest watershed in California; oak trees removed from 14% of land area
Lodge et al., 2002	589 mm/yr	evaporation dome	native pastures (89% of annual rainfall)
Lodge et al., 2001	514, 587, 572, 552, 637, 625 mm/yr	biophysical model	different pasture and grazing treatments
Malek et al., 1990	638 mm/yr	Bowen Ratio-Energy Balance, micrometeorological measurements	for Ranch in the middle of western, grass and shrub-covered margin of the playa
Moerlen *et al*., 1999	373.42 mm/yr	catchment water balance, Penman Monteith	25 km northwest of Cork, agricultural grassland, pasture and meadow, perennial ryegrass
Molchanov, 1973	300-370 mm/yr	water balance	meadow and clover
Molchanov, 1973	375-400 mm/yr	water balance	meadows in Sareevo (in Vologda district)
Morton, 1971	568 mm/yr	catchment water balance	pasture in Ausable catchment
Morton, 1971	464 mm/yr	catchment water balance	pasture in Pembina catchment
Morton, 1971	356 mm/yr	catchment water balance	pasture in Wascana catchment
Morton, 1971	578 mm/yr	catchment water balance	pasture in West Humber catchment
Morton, 1971	388 mm/yr	catchment water balance	pasture in Yorkton catchment
Morton, 1971	409 mm/yr	catchment water balance	pasture in Ribstone catchment
Morton, 1971	333 mm/yr	catchment water balance	pasture in Swift Current catchment
Morton, 1971	573 mm/yr	catchment water balance	pasture in Fish catchment
Morton, 1971	610 mm/yr	catchment water balance	pasture in Lynn catchment
Morton, 1983a	516 mm/yr	catchment water balance	pasture in Castor watershed, Canada
Morton, 1994	437 mm/yr	catchment water balance	Pasture in Whitemud watershed, Canada
Morton, 1994	392 mm/yr	catchment water balance	pasture in Magnusson watershed, Canada
Murphy et al, 2004	607, 641 mm/yr	evaporation dome	for continuous and rotational grazing
Nanni, 1970	750 mm/yr	catchment water balance	pasture in Cathedral catchment
Ni-Lar-Win, 1994	454 mm/yr	catchment water balance	pasture in Molenbeek 43 catchment
Ni-Lar-Win, 1994	510 mm/yr	catchment water balance	pasture in Molenbeek 44 catchment
Ni-Lar-Win, 1994	598 mm/yr	catchment water balance	pasture in Mark catchment
Ni-Lar-Win, 1994	480 mm/yr	catchment water balance	pasture in Ede catchment
Ni-Lar-Win, 1994	522 mm/yr	catchment water balance	pasture in Gr. Molenbeek catchment
Ni-Lar-Win, 1994	459 mm/yr	catchment water balance	pasture in Grote Nete catchment
Ni-Lar-Win, 1994	545 mm/yr	catchment water balance	pasture in Demer catchment
Ni-Lar-Win, 1994	572 mm/yr	catchment water balance	pasture in Gete catchment
Ni-Lar-Win, 1994	617 mm/yr	catchment water balance	pasture in Grote Gete catchment
Ni-Lar-Win, 1994	495 mm/yr	catchment water balance	pasture in Mandel catchment
Ni-Lar-Win, 1994	641 mm/yr	catchment water balance	pasture in Yin catchment
Nouvellon et al., 2000	289, 341, 459 mm/yr	soil water budget	Kendall site in Walnut Gulch experimental watershed
Novick et al., 2004	568 mm/yr	eddy covariance	grass-covered field, burned and mowed for hay
Olivier, 1961	1517 mm/yr	Olivier method	Malakal, Sudan, grass

continuation of Table E7. ET of grazing land

Paz *et al*., 1996	510 mm/yr	soil water balance	Gayoso-Castro farm in Castro de Ribeira de Lea (Lugo Province), Spain, grazed by sheep
Ridley et al., 1997	642, 619, 606 mm/yr	water balance	for phalaris, cocksfoot and ryegrass pastures
Roberts, 1998	329, 487, 240, 334 mm/yr	empirical relations from other studies	grazing land in England
Rosset *et al*., 2001	410 mm/yr	n/a	wet grassland in Swiss pre-alpine region, between 1273 and 1628 m above sea level, grazed and mown once a year
Scott & Sudmeyer, 1993	339 mm/yr	ventilated chamber technique	two perennial pastures (lucerne and phalaris) at a site near Collie in the southwest of Western Australia.
Sims, Singh & Laurenroth, 1978	200, 158 mm/yr	water balance	ALE (Washington) site, Northwest bunchgrass
Sims, Singh & Laurenroth, 1978	400 mm/yr	water balance	Bison (Montana) site, mountain grassland; moderate grazing intensity
Sims, Singh & Laurenroth, 1978	570, 280 mm/yr	water balance	Bridger (Montana) site, mountain grassland
Sims, Singh & Laurenroth, 1978	400, 620, 420 mm/yr	water balance	Cottonwood (South Dakota) site; mixed prairie; heavy grazing intensity
Sims, Singh & Laurenroth, 1978	460 mm/yr	water balance	Dickinson (North Dakota) site; mixed prairie; heavy grazing intensity
Sims, Singh & Laurenroth, 1978	450 mm/yr	water balance	Hays (Kansas) site; mixed prairie; moderate grazing intensity
Sims, Singh & Laurenroth, 1978	166, 200, 350 mm/yr	water balance	Jornada (New Mexico) site; desert grassland; lightly grazed
Sims, Singh & Laurenroth, 1978	500, 729, 670 mm/yr	water balance	Osage (Oklahoma) site; Tallgrass prairie; moderate grazing intensity
Sims, Singh & Laurenroth, 1978	250, 600, 400 mm/yr	water balance	Pantex (Texas) site; Shortgrass prairie; moderate grazing intensity
Sims, Singh & Laurenroth, 1978	250, 270, 320 mm/yr	water balance	Pawnee (Colorado) site; Shortgrass prairie; moderate grazing intensity
Shih & Snyder, 1985	1281-1424 mm/yr	n/a	Pasture
Silbertein et al., 1999	757 mm/yr	model	Wights catchment, within Collie River catchment, in southwest of Western Australia
Simpson et al., 1998	659 mm/yr	soil water budget	wallaby grass, subterranean clover pasture at Tamworth
Swift & Swank, 1980	1011 mm/yr	catchment water balance	pasture in Coweeta (13) catchment, NC
Vertessy, 1999	582 mm/yr	n/a	grasslands / pastures in south-eastern Australia
Waterloo *et al*., 1999	746 mm/yr	n/a	Fiji, converted from forest 100 years ago
Waterloo *et al*., 1999	860-980 mm/yr	n/a	typical grassland catchment in Fiji
Weltz & Blackburn, 1995	566-606 mm/yr	lysimeter	Prosopis – Acacia – Andropogon-Setaria Savannah; La Copita Research Area, eastern Rio Grande plain of Texas
Wohlfahrt et al., 2004	477.2, 490.4, 452.8 mm/yr	eddy covariance	this is a hay meadow - it is cut between two and three times a year, the hay is then used to feed the cows during winter when they're in the stable; cows graze at high elevation sites during summer
Wu *et al*., 2001	482.7 mm/yr	water balance model	originally grassland, after grazing now is covered with woody vegetation: Ashe, redberry juniper, live oak, vasey shin oak, and herbaceous plants; Cusenbary Draw Basin 209 km^2, Edwards Plateau, TX
Xu, 1992	774 mm/yr	catchment water balance	pasture in Leie catchment
Zubenok, 1976	300-350 mm/yr	n/a	treeless plains within the northern taiga subzone in Russia

continuation of Table E7. ET of grazing land

Zubenok, 1976	500-550 mm/yr	n/a	treeless plains in the mixed forests and forest steppe zones of European former USSR
Zubenok, 1976	475 (range 450-500 mm/yr)	n/a	treeless areas in the southern taiga subzone of the European former USSR; this estimate is supported by numerous water-balance investigations

Table E8. Annual evapotranspiration of impounded areas (reservoirs) (ET_i)

Source	ET	Method	Notes
Afansyev & Leksakova, 1973	341, 296 mm/yr	lake water balance	Lake Baikal
Ahmad, 1982	50-110 maf/yr	n/a	annual lake evaporation over Pakistan
Antal *et al*., 1973	860 mm/yr	energy balance and water balance	Lake Balaton, Hungary
Ballinger & Thornton, 1982	1541 mm/yr	class A evaporation pan	Lake McIlwaine, Rhodesia
Bastiaanssen & Bandara, 2001	1773 mm/yr	remote sensing	Tank in Kirindi Oya, Sri Lanka
Berger, 2001	63.64 in/yr	Bowen Ratio-Energy Balance, eddy correlation	over open water Ruby Lake National Wildlife Refuge Area, Ruby Valley, Northeastern Nevada
Braslavskii & Vikulina, 1963	605-619 mm/yr	water balance	forest zone, former USSR
Braslavskii & Vikulina, 1963	593-610 mm/yr	water balance	forest-steppe zone (eastern half), former USSR
Braslavskii & Vikulina, 1963	724-792 mm/yr	water balance	forest-steppe zone (western half), former USSR
Braslavskii & Vikulina, 1963	888-956 mm/yr	water balance	steppe zone (western half), former USSR
Braslavskii & Vikulina, 1963	865-938 mm/yr	water balance	steppe zone (eastern half), former USSR
Braslavskii & Vikulina, 1963	991-1130 mm/yr	water balance	zone of dry steppes and semi-deserts, former USSR
Braslavskii & Vikulina, 1963	1252-1363 mm/yr	water balance	desert zone, former USSR
Braslavskii & Vikulina, 1963	1505-1666 mm/yr	water balance	extreme south of central Asia, former USSR
Cherkasov *et al*., 1973	520 mm/yr	lake water balance	Lake Khubsugul (Kosogol), northern Mongolian People's Republic
Cleverly *et al*., 2002	74 cm/yr	3-d eddy covariance	Tamarix ramosissima; site on Sevilleta National Wildlife Refuge outside of San Acacia NM, no annual flooding, Rio Grande riparian areas, New Mexico
Cleverly *et al*., 2002	122 cm/yr	3-d eddy covariance	Bosque del apache NWR, flooded site; Rio Grande riparian areas, New Mexico
Cohen et al., 2002	1729 +/- 64 mm/yr	Penman-Monteith	for Bet Dagan, Israel
Farnsworth *et al*., 1982	0.6-0.8 m/yr	field data using the Bowen method	northeastern United States
German, 2000	57.4, 53.1 in/yr	Bowen Ratio-Energy Balance	two open water sites in Florida Everglades
German, ER., unpublished	53.22-55.54 in/yr	Bowen Ratio-Energy Balance	two open water sites in Florida Everglades
Griffiths, 1972	2087, 2160 mm/yr	CRLE model	Lake Nasser, at Wadi Halfa

continuation of Table E8. ET of reservoirs

Hirota, 2001	760-815 mm/yr	heat balance model and Force-Restore method	open water near lawn from routine meteorological data at Chiang Mai in the Chao Phraya river basin in Thailand
Hirota, 2001	1080-1140 mm/yr	heat balance model and Force-Restore method	open water near bare areas in Bangkok from routine meteorological data in the Chao Phraya river basin in Thailand
Hurst & Philips, 1931	1.9 mm/day	atmometer	Sakha
Hurst & Philips, 1931	2.3 mm/day	atmometer	Cairo (Ezbekiya)
Hurst & Philips, 1931	2.8 mm/day	atmometer	Giza
Hurst & Philips, 1931	5.4 mm/day	atmometer	Helwan
Hurst & Philips, 1931	4.2 mm/day	atmometer	Tor
Hurst & Philips, 1931	4.1 mm/day	atmometer	Qasr el-Gebali
Hurst & Philips, 1931	3.3 mm/day	atmometer	Minya
Hurst & Philips, 1931	7.5 mm/day	atmometer	Aswan
Hurst & Philips, 1931	8.6 mm/day	atmometer	Atbara oasis
Hurst & Philips, 1931	4.9 mm/day	atmometer	Port Sudan oasis
Hurst & Philips, 1931	7.5 mm/day	atmometer	Kartoum
Hurst & Philips, 1931	5.4 mm/day	atmometer	Kassala
Hurst & Philips, 1931	5.1 mm/day	atmometer	Gallabat
Hurst & Philips, 1931	6.5 mm/day	atmometer	Wad Medani
Hurst & Philips, 1931	5.3 mm/day	atmometer	Roseires
Hurst & Philips, 1931	6.9 mm/day	atmometer	Dueim
Hurst & Philips, 1931	6.7 mm/day	atmometer	El-Obeid
Hurst & Philips, 1931	5.8 mm/day	atmometer	El Fasher
Hurst & Philips, 1931	4.5 mm/day	atmometer	Malakal
Hurst & Philips, 1931	3.7 mm/day	atmometer	Wau
Hurst & Philips, 1931	3.0 mm/day	atmometer	Mongalla
Hurst & Philips, 1931	3.6 mm/day	lake water balance	Lake Victoria
Hurst & Philips, 1931	2.2 mm/day	atmometer	Quarahiya
Hurst & Philips, 1931, Shahin, 1985	4.5, 5.5, 7.9 mm/day	atmometer, Penman, Hargreaves	The Nile near Assiut
Hurst & Philips, 1931, Shahin, 1985	7.9 mm/day	atmometer	Wadi-Halfa oasis
Hurst & Philips, 1931, Shahin, 1985	8.4 mm/day	atmometer	Merol oasis
Hurst & Philips, 1931, Shahin, 1985	3.0-3.5 mm/day	atmometer	Lake Tana
Hurst, 1952	2.3 mm/day	atmometer	Nile Delta
Hurst, 1952	2.8 mm/day	atmometer	Cairo and neighbourhood
Hurst, 1952	4.0 mm/day	atmometer	Fayum
Hurst, 1952	4.5 mm/day	atmometer	Upper Egypt
Hurst, 1952	7.8 mm/day	atmometer	Kartoum
Hurst, 1952	3.9 mm/day	atmometer	Lake Albert
Hurst, 1952	3.9 mm/day	atmometer	Lake Edward
Hurst, 1952	3.8 mm/day	lake water balance	Lake Victoria
Keig *et al*., 1979	1545 (SD 186) mm/yr	Penman Evaporation	17 stations in Papua New Guinea, based on data from US Class A pan evaporimeters; Papua New Guinea
Knox & Nordenson, undated, from Wood, 1978	883000 m2	water balance	West Canada Lake
Kobayashi, 1973, Yoshino (?)	1099, 964, 1062, 982, 1468, 1326, 1399 mm/yr	Pan, Penman, Fitzpatrick, Swinbank	Open water evaporation for Tateno, Japan
Kobayashi, 1973, Yoshino (?)	1319, 1510, 1976, 1906 mm/yr	Pan, Penman, Fitzpatrick, Swinbank	Open water evaporation for Pleiku, Vietnam

continuation of Table E8. ET of reservoirs

Kobayashi, 1973, Yoshino (?)	1997, 1915, 2296, 2186 mm/yr	Pan, Penman, Fitzpatrick, Swinbank	Open water evaporation for Qui-Nhon Vietnam
Kobayashi, 1973, Yoshino (?)	1660, 1589, 2045, 1957 mm/yr	Pan, Penman, Fitzpatrick, Swinbank	Open water evaporation for Lien-Khuong, Dalat, Vietnam
Kobayashi, 1973, Yoshino (?)	1778, 1968, 2372, 2267 mm/yr	Pan, Penman, Fitzpatrick, Swinbank	Open water evaporation for Saigon, Tansonnhut, Vietnam
Kohler, Nordenson & Baker, 1959	33 inches	n/a	average annual lake evaporation
Kotwicki & Clark, 1991	1899 mm/yr	field measurements from lake surface	arid climate lake; Lake Eyre, Australia
Kotoda & Mizuyama, 1984	700-800 mm/yr	heat balance, aerodynamic method	Lake Biwa, in the centre of Honshu Island
Krishnamurthy & Ibrahim, 1973	3.65-4.5 mm/day	lake water balance	Lake Victoria
Kullus, 1973	570 mm/yr	lake water balance	Lake Peipsi-Pihkva, Estonia
Laczniak et al., 1999	8.6 feet	Walker and Eakin (1963)	Peterson Reservoir, Ash Meadows Area, Nye County, Nevada
Lapworth, 1965	662 mm/yr	n/a	reservoir near London
Liu & Kotoda, 1998	786.3 mm/yr	Kotoda 1986 and Advection-Aridity (Brutsaert and Stricket, 1979) models, eddy correlation	water surface, NW China, middle part of Hexi corridor
Marsh & Bigrass, 1988 Marsh, 1991	339, 388 mm/yr	Priestley-Taylor, micrometeorological, lake water balance, model	NRC lake, Mackenzie Delta
Meyer, 1942	14-100 inches per year	n/a	mean annual evaporation from shallow lakes and reservoirs, computed from 50 years of weather bureau records for USA
Morton, 1983	691, 712 mm/yr	water budget	Last Mountain Lake, Saskatchewan, Canada
Morton, 1983	673 mm/yr	CRLE model	Dauphin Lake
Morton, 1983	1580 mm/yr	CRLE model	Lake Victoria
Morton, 1983	720 mm/yr	CRLE model	Last Mountain Lake, Saskatchewan, Canada
Morton, 1983	1805 mm/yr	CRLE model	Salton Sea
Morton, 1983	740 mm/yr	CRLE model	Lake Ontario
Morton, 1983	2022 mm/yr	CRLE model	Silver Lake
Morton, 1983	1195 mm/yr	CRLE model	Utah Lake
Morton, 1983	1245 mm/yr	CRLE model	Lake Hefner
Morton, 1983	1290 mm/yr	CRLE model	Winnemucca Lake
Morton, 1983	1280 mm/yr	CRLE model	Pyramid Lake
Movahed-Danech, 1973	1382, 1394 mm/yr	from lake surface	Lac de Rezeieh, northwest Iran
Nehaichik, 1973	420 mm/yr	assume lake water balance	Lake Ilmen, Russia
Nehaichik, 1973	490 mm/yr	assume lake water balance	Lake Khanka, China / Russia
Nehaichik, 1973	710 mm/yr	assume lake water balance	Lake Kulundinskoye, Russia
Nijssen & Lettermaier, 2002	599, 585, 617 mm/yr	water balance	White Gull Creek Basin, England
Omar & El Bakry, 1981	2689 mm/yr	water balance	Lake Nasser, Egypt
Prata, 1989	2190 +/- 100 mm	RS	arid climate lake
Richter, 1985	633-843 mm/yr	evaporation pans, empirical relations	Lake Stechlin
Richter, 1973	712 mm/yr	energy balance method	Lake Muritz, Germany
Riehl, 1979	280 cm/yr	n/a	annual evaporation loss for Lake Nasser, in Egypt
Sacks *et al*., 1994	151 cm/yr	energy budget	Lake Barco in North Central Florida
Sacks *et al*., 1994	128 cm/yr	energy budget	Lake Five-O in Florida Pan Handle
Shahin, 1985	6.6 mm/day	pan conversion	Lake Victoria at Kisumu
Shahin, 1985	3.4 mm/day	pan conversion	Lake Victoria
Shahin, 1985	5.4, 6.3, 9.0 mm/day	Penman, Hargreaves, Piche	Malakal
Shahin, 1985	5.8, 6.2, 7.6 mm/day	Penman, Hargreaves, Piche	Wau

continuation of Table E8. ET of reservoirs

Shahin, 1985	5.5, 5.0, 7.0 mm/day	Penman, Hargreaves, Piche	Mongalla, Juba
Shahin, 1985	8.04 mm/day	pan, Panman, Piche, Kohler	The Nile at Khartoum
Shahin, 1985	4.3 mm/day	pan, Panman, Piche, Kohler	The Nile at Gambeila
Shahin, 1985	5.3 mm/day	pan, Panman, Piche, Kohler	The Nile at Akobo
Shahin, 1985	5.0, 7.1 mm/day	pan, Panman, Piche, Kohler	The Nile near Addis Abbaba
Shahin, 1985	6.3, 7.9 mm/day	pan, Panman, Piche, Kohler	The Nile near Roseires
Shahin, 1985	7.0, 9.2 mm/day	pan, Panman, Piche, Kohler	The Nile near Wad Medani
Shahin, 1985	7.0 mm/day	pan, Panman, Piche, Kohler	The Nile near Singa
Shahin, 1985	7.4 mm/day	pan, Panman, Piche, Kohler	The Nile near Sennar
Shahin, 1985	5.3 mm/day	pan, Panman, Piche, Kohler	The Nile near Kurmuk
Shahin, 1985	8.0 mm/day	pan, Panman, Piche, Kohler	The Nile near Atbara
Shahin, 1985	5.8, 8.7, 7.7 mm/day	pan, Panman, Piche, Hargreaves	The nile at Qena
Shahin, 1985	6.1, 8.6, 14.7 mm/day	pan, Panman, Piche, Hargreaves	open water at Kharga oasis
Shahin, 1985	4.9, 7.0, 9.8 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Almaza (airport)
Shahin, 1985	5.2, 6.7, 9.3 mm/day	pan, Panman, Piche, Hargreaves	Suez Canal
Shahin, 1985	4.4, 6.2, 3.7 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Zagazig
Shahin, 1985	3.8, 5.3, 4.5 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Tanta
Shahin, 1985	4.0, 4.2, 5.1 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Edfina
Shahin, 1985	4.6, 4.0, 8.0 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Port Said (airport)
Shahin, 1985	4.4, 4.0, 5.0 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Alexandria
Shahin, 1985	4.9, 4.7, 7.9 mm/day	pan, Panman, Piche, Hargreaves	the Nile near Sallum (observatory)
Shahin, 1985	2033 mm/yr	Penman	open water evaporation for Shambe in the Sudd region
Shahin, 1985	4.7, 3.8, 7.8 mm/day	pan, Panman, Piche, Hargreaves	the Nile near El Kasr
Shahin, 1985	4.5, 4.2, 4.6 mm/day	pan, Panman, Piche, Hargreaves	the Nile near El Sirw
Shahin, 1985	4.3, 5.2, 7.7 mm/day	pan, Panman, Piche, Hargreaves	the Nile near El Tahrir
Shnitnikov, 1973	970 mm/yr	n/a	Lake Aral, desert location
Shnitnikov, 1973	950-1047 mm/yr	n/a	Lake Balkhash, arid steppe , semi-desert
Shnitnikov, 1973	702 mm/yr	n/a	Lake Issyk-kul, intermountain location
Solantie, 1973	390-610 mm/yr	empirical Dalton formula	Finland
Stewart & Rouse, 1976		n/a	
Tattari & Ikonen, 1997	400 mm/yr	ASTIM model	for open water surface in Hietajärvi, Finland
Telzaff & Adams, 1983	2150-2640 mm/yr	water balance	n/a
Tyler *et al.*, 1997	2.7 (SD 0.68) mm/day	eddy correlation, microlysimeters	seasonally adjusted evaporation rate for open water at Owens Lake, California
Unland *et al.*, 1998	1.705 m/yr	micrometeorological measurements, Bowen Ratio-Energy Balance	open water surfaces
USGS, 1958 Morton, 1983	1855-2163 mm/yr	energy budget, CRLE model	Lake Mead on the Colorado River
Vali-Khodjeini, 1991 Patkovich, 1986 Privalskii, 1981; Shiklomanov & Geogievskii, 1981	745 mm/yr	water budget	Caspian Sea
Van Dijk *et al.*, 2001	1300 mm/yr	water balance, micrometeorological measurements, literature	open water in Ciumutuk river catchment, West Java, Indonesia
Vallet-Coulomb *et al.*, 2001	1780, 1870, 1730, 1740 mm/yr	lake energy balance, Penman method, CRLE model, chloride budget	Lake Ziway, Ethiopia
Verburg & Hecky, 2002	115-173 W/m2/yr	energy balance	poster at AGU, for Lake Tanganyika in Central Africa (between Tanzania and Congo), Energy balance
Vischer & Hughes, 1978	120 cm/yr	n/a	Florida Lakes

continuation of Table E8. ET of reservoirs

Zamanov, 1973	300 mm/yr	lake water balance	Great Alagel Lake
Zubenok, 1976	160 cm/yr	energy balance	30^{o}N to 30^{o}S
Zubenok, 1976	100 cm/yr	energy balance	30-60 degrees latitude, potential ET

Table E9. Annual evapotranspiration of tree plantations (ET_{tp})

Source	ET	Method	Description
Bailly *et al*., 1974	1610 mm/yr	soil water balance	Manankazo, Madagascar, pinus patula plantation, 4-10 yrs
Blackie, 1979	1160 mm/yr	catchment water balance	Kimakia, Kenya, Pinus Patula plantation., 10-16 yrs
Bruijnzeel, 1988	1070 mm/yr	catchment water balance	11-35 year old plantation forest of Agathis dammara Warb in central Java
Bruijnzeel, 1988	900 mm/yr	water balance	29 year old plantation, Pinus merkussi plantation, Genteng, West Java
Bubb & Croton, 2002	1082-1124 mm/yr	catchment water balance	exotic pine plantation in previously mixed area
Buttle & Metcalfe, 2000	358-525 mm/yr	catchment water balance	Partially clear-cut forests; total area is about 40,000 km^2. obtained from residual of water balance; for six watersheds in Ontario; equal to average of 6 watersheds (441 mm)
Calder, 1992	3400 mm/yr	n/a	young Eucalyptus forests, 8 m deep soils
Cornish & Vertessy, 2001	1100 mm/yr (SD 78)	catchment water balance	8 different catchments in Karuah Research Area, of Eucalypt forests in New South Wales, Australia
Dunin & Aston, 1984	766-933 mm/yr	model: corroborated by weighing lysimeter data	Eucalypt regrowth in Kioloa State Forest in Australia.
Dunn & Mackay, 1995	338 (SD = 16.0) mm/yr	model, based on Penman-Monteith with Rutter interception	felled forest in the Tyne Basin in North East England
El-Nokrashy, 1963	1121.10, 1085.80 mm/yr	n/a	Citrus trees in Delta Barrage, Egypt
Ewel & Gholz, 1991	74-111 cm/yr	simulated ET	pine plantation range from dry to wet year
Gholz & Clark, 2002	959, 951, 1110 mm/yr	eddy covariance	along chronosequence of slash pine plantation in Florida: recent clear-cut, mid-rotation, and 24-yr old rotation stand
Greenwood et al., 1985	2300, 2700 mm/yr	VC	for young Eucalyptus plantation, 3 sites,
Holscher *et al*., 1997	1364 mm/yr	micrometeorological measurements	plot in a 2.5 year old plot in Eastern Amazonia.
Jaeger & Kessler, 1997	622 mm/yr	micrometeorological measurements, water balance	33 year old pine plantation in upper Rhine watershed, Southern Germany, subject to thinning
Jordan & Fischer, 1977	38.3+2.4 in/yr	"hydrologic means"	Turpentine Run, St. Thomas Virgin Islands
Klinge et al., 2001	130.333	soil water balance, model, Pman	Federal Cacao Research Institute, for tropical lowland rainforest, ET for forests year of and year after clearcutting
Krestovsky, 1969b	530, 580, 540, 570 mm/yr	n/a	40 & 60 year old pine and spruce forest in southern taiga subzone of European former USSR
Krestovsky, 1969b	310, 350, 445, 550, 590 mm/yr	n/a	5, 10, 20, 40, 60 year old deciduous forest in southern taiga subzone of European former USSR
Krestovsky, 1980	305-380 mm/yr	n/a	regrowth areas, aged 1-5 and 10-15 years, in the southern taiga subzone in the European former USSR
Lane et al., 2004	1118, 1150, 969, 1024 mm/yr	soil water balance	Eucalyptus plantation, south-eastern China

continuation of Table E9. ET of tree plantations

Law, 1957	711 mm	lysimeter	0.045 ha plantation of Sitka spruce in Hodder catchment,
Le Maitre & Versfeld, 1997	1180.9, 1031.0, 1176.5, 941.2, 1133.0, 1119.0, 1108.1 mm/yr	water balance, meteorological data	catchments afforested with Pinus patula and Pinus radiata; each number represents a different catchment
Liu *et al*., 1998	795 (+/- 20) mm/yr	ET model with micrometeorological measurements, eddy correlation, class A pans,	pine plantations in industrial forest lands of the Georgia-Pacific Corporation15 km NE of Gainesville FL
Löfgren, 2004a,b	520, 531, 552, 570, 544, 629 mm/yr	micrometeorological measurements	Station SE04 - Gardsjon, Norway Spruce Forest. Probably grazed woodland for centuries before clear-felling 1900-1910 and subsequent forest tree planting and thinning (1968). Grazing was suspended around 1950. In 1980 roughly a half hectare was clear-felled
Löfgren, 2004a,b	400, 452, 453, 522, 471, 537 mm/yr	micrometeorological measurements	Station SE14 Aneboda, Norway Spruce. Grazed woodland for centuries. Probably clear-felled in the 1860´s, then abandoned and overgrown. Grazing suspended in the 1930´s. Light thinning in the 1940´s and in 1950.
McMahon et al., 1996	871, 794, 682, 650 mm/yr	model	Eucalyptus globulus research plots, long-term mean climate factors, derived from Esoclim model, planted 1983, at Esperance (sites 1-4)
McMahon et al., 1996	1627 mm/yr	model	Eucalyptus globulus research plots, long-term mean climate factors, derived from Esoclim model, planted 1984, at Darkan
McMahon et al., 1996	1247 mm/yr	model	Eucalyptus globulus research plots, long-term mean climate factors, derived from Esoclim model, planted 1984, at Manjimup
McMahon et al., 1996	1262 mm/yr	model	Eucalyptus globulus research plots, long-term mean climate factors, derived from Esoclim model, planted 1986, at Northcliffe
McMahon et al., 1996	962 mm/yr	model	Eucalyptus globulus research plots, long-term mean climate factors, derived from Esoclim model, planted 1990 at Forcett
Moran & O'Shaughnessy, 1984	1189 mm/yr	catchment water balance	34 year old Eucalypt tree plantation forest in Monda 1-3 catchments, Australia
Murai, 1980 Tsukamoto, 1992	532 mm/yr	water balance	New Cypress Plantation
Murakami *et al*., 2000	389 mm/yr (SD 75.4)	catchment water balance	immature Japanese cypress and cedar forests
Nijssen & Lettenmaier, 2002	279, 287, 292 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	medium-age regeneration conifer forest in the White Gull Creek Basin, Saskatchewan, Canada.
Nijssen & Lettenmaier, 2002	212, 226, 229 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	new regeneration conifer forest in the White Gull Creek Basin, Saskatchewan, Canada.
Nijssen & Lettenmaier, 2002	345, 360, 381 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models	medium-age regeneration deciduous forest in the White Gull Creek Basin, Saskatchewan, Canada.
Nijssen & Lettenmaier, 2003	337, 356, 376 mm/yr	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of	new regeneration deciduous forest in the White Gull Creek Basin, Saskatchewan, Canada.

continuation of Table E9. ET of tree plantations

		multiple regression models	
Pilgrim et al., 1982	655 mm/yr	catchment water balance	pine plantation
Pudjiharta, 1986a	1655, 1978 mm/yr	lysimeter	Ciwidey West Java, Pinus merkusii plantation, 1-8 year, 9-17 year
Richardson, 1982	2000 mm/yr	catchment water balance	Pinus caribaea plantation, 18 yrs, Blue Mountains, Jamaica (leaky catchment)
Richardson, 1982	1849, 1365, 485 mm/yr	catchment water balance	19 year old stand of pinus caribaea in Jamaica; comparison of the water balance of two but predominantly impermeable catchments, one covered with pine plantation, the other with lower montane rainforest
Riekerk, 1985	77-118 cm/yr	n/a	watersheds dominated by pine plantations in north Florida
Rosenzweig, 1968	log 3.09 mm/yr	Thornthwaite method	secondary tropical forest, Kade, Ghana
Running *et al.*, 1989	35-39 cm/yr	simulation model (FOREST-BGC)	predominantly coniferous forests in western Montana, the part of the study area that was heavily clearcut
Rutter, 1964	1.02 mm/yr	soil water balance	plantation of Pinus sulvestris at Crowthorne Berks.
Schafer *et al.*, 2002	537.1, 575, 614.3 mm/yr	sap flux, hydrological balance, eddy covariance	Duke Forest Loblolly pine plantation (15 yr old)
Shahin, 1959	977.79-964.45 mm/yr	n/a	Citrus trees in Giza, Egypt
Shahin, 1985	1215 mm/yr	micrometeorological, Doorenbos & Pruitt 1977 method	citrus trees for Cairo, Egypt
Shimizu et al., 2003	902, 875 mm/yr	eddy covariance and water balance	Kahoku experimental watershed, cypress plantation
Sommer *et al.*, 2002	1421 mm/yr	Bowen Ratio-Energy Balance	secondary woody vegetation in Brazilian Amazon - a 3.5 year old vegetation
Sun et al., 1998	901 mm/yr	model	typical flatwoods sites ; Gator National Forest, and Bradford Forest
Sun *et al.*, 2002	1077 (SD 98) mm/yr	water balance	140 ha Florida watershed - unmanaged mature cypress-plantation
Sun *et al.*, 2002	1054 (SD 96) mm/yr	water balance	mature loblolly pine plantation in coastal North Carolina
Thornton *et al.*, 2002 Law *et al.*, 2002	0.686, 0.664 m/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	Blodgett forest, California; clearcut 1990
Thornton *et al.*, 2002; Law *et al.*, 2002	0.528, 0.482 m/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	Duke Forest, North Carolina, 1983 clear cut
Thornton *et al.*, 2002; Law *et al.*, 2002	0.988 m/yr	coupled water-carbon-nitrogen model, canopy-scale flux observations	slash pine plantation, Gainesville, Florida, clearcut 1990
Tiktak & Bouten, 1994	712 mm/yr	micrometeorological measurements model	stand 29 years old at 1988; last thinning carried out 5 years before measurements
Van Dijk et al., 2001	1250 mm/yr	water balance, micrometeorological measurements, literature	for Paraserianthes plantation in Cikumutuk river catchment,
Vertessy *et al.*, 1996	798 mm/yr	ecohydrological water balance model (Topog-IRM)	mountain ash Picaninny (0.53 km^2) forest catchment, Victoria, Australia; clear-felled and seeded with mountain ash
Vertessy *et al.*, 1998	1220, 1280, 1340 mm/yr	SAP, microlysimeter, humidity dome, stemflow	15, 30 and 60 year old mountain ash forest in Maroonda Catchments, New South Wales, Australia
Vertessy *et al.*, 2001	1371 mm/yr	SAP, lysimeter	15-year old ash / eucalyptus forest in Victoria, Australia
Vorosmarty & Wilmott, 2002	1194, 1210, 1260, 1263, 1180 mm/yr	WBM/WTM computed water balance	Amazon basin, upriver of Obidos, Brazil; water-year begins in September

continuation of Table E9. ET of tree plantations

Waterloo *et al.*, 1999	1926, 1717 mm/yr	micrometeorological measurements, TVEB	6 and 15 year old pinus caribaea plantations on former grassland soils under maritime tropical conditions; from model, former grassland soils
Waterloo, 1994	1772 mm/yr	n/a	vigorously growing young pine plantation in Fiji
Whitehead & Kelliher, 1991	796-997 mm/yr	Penman-Monteith, catchment water balance, soil water balance, RI, RAU	11-year old pinus radiata stand before and after thinning, at Longmile Rotorua, New Zealand
Wilson *et al.*, 2000	1340 MJ/m^2	eddy covariance	mixed deciduous stand over 50 years old, having regenerated from agricultural land; temperate deciduous forest in Oak Ridge TN
Zakia, 1987	615 mm/yr	soil water balance	Minas Gerais, Brazil, Pinus caribaea plantations, 4-6 yrs
Zakia, 1987	785 mm/yr	soil water balance	Minas Gerais, Brazil, eucalyptus grandis plantations, 4-6 yrs

Table E10. Annual Evapotranspiration of Wetlands (ET_w)

Source	ET	Method	Notes
Abtew, 1996	3.6 mm/day	water balance, lysimeter	constructed wetlands; cattaill, mixed marsh vegetation, open water
ADWR, 1991	1271-1198 mm/yr	Blaney-Criddle	riparian area in the San Pedro River Basin, Sierra Vista sub watershed
Balek, 1977	2180 mm/yr	n/a	Bangweulu swamp in Luapula catchment of the Upper Congo (Zaire)
Balek, 1977	1005 mm/yr	n/a	Kafue Flats, in Zambezi river, in Zambia
Bawazir et al., 2004	3222 MJ/m2/yr	eddy covariance	riparian saltcedar, along Rio Grande River
Berger, 2001	50.24 in/yr	Bowen Ratio - Energy Balance, eddy covariance	moderate to dense cover of bulrush marsh Ruby Lake National Wildlife Refuge Area, Ruby Valley, Northeastern Nevada
Bidlake *et al.*, 1996	970-990 mm/yr	Bowen Ratio - Energy Balance	cypress swamp and marsh in west-central Florida
Cleverly *et al.*, 2002	122 cm/yr	eddy covariance	Tamarix ramosissima; for site at Bosque del apache National Wildlife Refuge, flooded site; Rio Grande riparian areas, New Mexico
Culler *et al.*, 1982	1090 mm/yr	soil water balance	phreatophytes
Dolan *et al.*, 1984	131.7 cm/yr	using diurnal water-table fluctuation method	Palatkaha watershed swamp, Florida; mixed emergent aquatic macrophyte community
Eaton & Rouse, 2001	198 mm	soil water balance, energy balance	Assuming minimal ET in winter. For a subarctic sedge fen
Ewel & Smith, 1992	38, 60, 86 cm/yr	water balance	range 38 - 86 cm/yr
Fieldler & Sommer, 2004	500-800 mm/yr	micrometeorological measurements	natural wetlands in the Allgau region of southwest Germany
Finnish Environmental Institute, 2004	300-350 mm/yr	n/a	wetland forest in River Simojoki basin, Northern Boreal zone in Finland
Gatewood et al., 1950	1.829 m/yr	water balance	in lower Gila River valley, riparian water use estimates
German & Sumner, 2001	43.5 and 55.7 in/yr	micrometeorological measurements	meteorological methods, one for a blue cypress marsh and one for everglades national park
German, 2000	45.7, 45.4, 47.9, 48.5, 50.4, 42.1, 42.5 in/yr	Bowen Ratio - Energy Balance	7 sites in the Everglades, ranging from cattails to sawgrass and rushes

continuation of Table E10. ET of wetlands

German, ER, unpublished	43.73, 45.68, 50.05, 46.0, 50.50, 43.44, 42.78 in/yr	Bowen Ratio - Energy Balance	7 sites in the Everglades, ranging from cattails to sawgrass and rushes
Hicks et al., 2001	350-500 mm/yr	estimate from other ET estimates	paper states that there are no known ETw measurements in NZ
Hughes *et al*., 2001	700 mm/yr	eddy covariance, Pan Evaporation, Penman-Monteith	small eddy correlation dataset, for Kikuyu grass wetlands
Hurst, 1952	6.5 mm/day	atmometer	oases
Hurst, 1952	6.1 mm/day	water balance	swamps near Lake Kyoga
Knowles, 1996	37.9 and 37.6 in/yr	regional water budget, modified Priestley Taylor model, Eddy Correlation	Rainbow Springs and Silver Springs basins in North Central Florida
Koranda *et al*., 1978	185 mm/yr	n/a	wet meadow: sedge moss, dominates coastal plain of Alaska and former USSR, limited presence in sub arctic
Krestovsky, 1969b	490 mm/yr	n/a	marshy areas in southern Taiga subzone of former USSR
Laczniak et al., 1999	2.6 feet	Walker and Eakin (1963)	Bole Spring, Ash Meadows Area, Nye County, Nevada
Laczniak et al., 1999	3.44 feet	Walker and Eakin (1963)	Carson Meadow, dense wetland vegetation, Ash Meadows Area, Nye County, Nevada
Laczniak et al., 1999	3.73 feet	Walker and Eakin (1963)	Fairbanks meadow, dense grassland, intermittently flooded, Ash Meadows Area, Nye County, Nevada; based on less than one year of data
Laczniak et al., 1999	3.91 feet	Walker and Eakin (1963)	Fairbanks swamp dense wetland vegetation, Ash Meadows Area, Nye County, Nevada
Laczniak et al., 1999	2.58 feet	Walker and Eakin (1963)	Lower Crystal Flat, flooded bare soils with some grass, Ash Meadows Area, Nye County, Nevada
Laczniak et al., 1999	3.23 feet	Walker and Eakin (1963)	flooded grassland, Rogers Spring, Ash Meadows Area, Nye County, Nevada
Liu *et al*., 1998	974 (+/- 86) mm/yr	model with field micrometeorological measurements, eddy correlation, class A pans,	cypress wetlands in industrial forest lands of the Georgia-Pacific Corporation
Mao, 2002	3.21, 3.25, 3.66, 3.53 mm/day	lysimeter, pan, micrometeorological measurements, Penman Monteith, Priestley Taylor	areas dominated by wetland vegetation; St. Johns River Basin
Miller, 1983	240 mm/yr	n/a	peatlands in arctic areas
Nature Consultants, 2004	437 mm/yr	n/a	average wetland ET for Ireland
Nijssen & Lettenmaier, 2002	489, 502, 496 mm/yr	eddy covariance, Bowen-Ratio Energy Balance, Penman Monteith	extrapolation of eddy correlation and bowen ratio methods to basin using Penman-Monteith combination equation and LAI weighted versions of multiple regression models; for fen
Olivier, 1961	4.7 mm/day	n/a	swamp around Soroti near the northern shore of Lake Kyoga
Oyebande & Balek, 1989	1075 mm/yr	n/a	dambo wetland in Zambia
Petrone *et al*., 2000	218 mm/yr	Bowen Ratio Energy Balance, eddy correlation using a vertical propeller anemometer	northern Canada, high subarctic wetland tundra region near the shores of Hudson Bay, in central subarctic 26 km east of Churchill, Manitoba; assume no ET during winter months in subarctic
Petrone *et al*., 2000	216 mm/yr	Bowen Ratio Energy Balance, eddy correlation using a vertical propeller anemometer	northern Canada, western subarctic wetland tundra 56 km northeast of Inuvik, NWT; assume no ET during winter months in subarctic
Porcher, 1981	1011 mm/yr	n/a	Francis-Beidler Forest, Four Holes Swamp in Coastal Plain of South Carolina
Roberts, 1998	320-407 mm/yr	empirical relations	wet moorland

continuation of Table E10. ET of wetlands

Rockstrom *et al*., 1999	221 (range 200-260) mm/yr	compilation of secondary	3 literature sources; for "boreal bog"
Rockstrom *et al*., 1999	674 (range 456-1020) mm/yr	compilation of secondary	4 literature sources; for "temperate bog"
Rockstrom *et al*., 1999	843 (range 670-720) mm/yr	compilation of secondary	3 literature sources; for "temperate swamp"
Rockstrom *et al*., 1999	1127 (range 930-1277) mm/yr	compilation of secondary	5 literature sources; for "subtropical swamp"
Rockstrom *et al*., 1999	1656 (range 1408-1904) mm/yr	compilation of secondary	1 literature source; for "tropical swamp" (low / high values are based on the mean +/- 15%)
Romanov, 1968	331 mm/yr	thermal balance method	sphagnum bogs with dwarf shrubs
Romanov, 1968	410 mm/yr	thermal balance method	entire bog catchment area
Romanov, 1968	411 (SD 29 mm) mm/yr	thermal balance method	lowmoor bogs
Roulet & Woo, 1986	217 mm/yr	n/a	wetland in Baker Lake, NWT; assuming no evaporation during snow period
Rouse, 2000	400 mm/yr	energy balance	
Shahin, 1985	4.1 mm/day	n/a	Machar Swamps in the Sobat Basin, Ethiopia
Sharma, 1988	1800 mm/yr	n/a	Lukanga swamp, Zambia
Stewart, 1989	3.5 mm/day	remote sensing and micrometeorological measurements	Chizengeni dambo, in the Nyatsime catchment
Sumner, 2002	1314-1416 mm/yr	eddy covariance	2 year period, sawgrass peat marsh marshes in Florida, measured before, during and after two droughts, sites were burned at one point
Tomlinson, 1996	434.1 (+ 11) mm/yr	Bowen-Ratio Energy Balance, Penman Monteith, lysimeter	missing one month data, added min monthly value as estimate; meadow site Turnbull Meadow, Spokane and Yakima County, Washington State, USA
UNEP, 1992	2400mm/yr	n/a	wetlands of the river Niger
Unland et al., 1998	1.697 m/yr	Bowen-Ratio Energy Balance, micrometeorological measurements	for riparian area of Santa Cruz River in southern Arizona

Table E11. Global annual terrestrial evapotranspiration (*TET*)

Source	TET	Notes
Arora & Boer, 2002	461 mm/yr	GCM based analysis of temperature variation in soil moisture
Arora, 2001	73,000 km^3/yr	AMIPII Run of 3rd Generation General Circulation Model of the Canadian Centre for Climate Modelling and Analysis
Baumgartner & Reichel, 1975	71,000 km^3/yr	distribution maps of actual ET according to Thornthwaite, and on determined difference between runoff and precipitation for individual river basins (hydrographic method). The former provides a relative distribution picture of ET. original data set
Berner & Berner, 1987	72,900 km^3/yr	water balance methods; estimates of precipitation on land are from L'Vovich, 1973, and runoff from land from Baumgartner and Reichel, 1975 and groundwater discharge from Meybeck, 1986
Desborough *et al*., 2001	40.0 mm/month	GCM simulation (SLAM model); may not be independent with other 4 measures; assuming terrestrial area is 140x10^{12} m^2; for 60°S to 90°N
Desborough *et al*., 2001	41.9 mm / month	GCM simulation (SLAM-IT model); may not be independent with other 4 measures; assuming terrestrial area is 140x10^{12} m^2; for 60°S to 90°N
Desborough *et al*., 2001	42.1 mm / month	GCM simulation; assumed surface resistance of 150 s/m (RS-GI model); may not be independent with other 4 measures; assuming terrestrial area is 140x10^{12} m^2; for 60°S to 90°N

continuation of Table E11. Total terrestrial evapotranspiration

Desborough *et al*., 2001	39.0 mm/ month	GCM simulation; assumed surface resistance of 150 s/m (RS-I model); may not be independent with other 4 measures; assuming terrestrial area is $140x10^{12}$ m^2; for 60°S to 90°N
Desborough *et al*., 2001	38.6 mm/month	GCM simulation; assumed surface resistance of 25 s/m (RS model); may not be independent with other 4 measures; assuming terrestrial area is $140x10^{12}$ m^2; for 60°S to 90°N
Korzoun (ed). UNESCO, 1974/78	72,000 km^3/yr	original data set; monthly values of ET from land were computed with help of Budyko complex method that is based on the combined solution of the heat and water balance equations and empirical relation between ET rate and soil moisture content
L'Vovich, 1973b	71,745 km^3/yr	cited in Mather, 1992, Berner & Berner, 1987; Brutsaert, 1982
Legates & Mather, 1992	553 mm/yr	precipitation data from Legates, 1987, accounting method
L'Vovich, 1972	72,100 km^3/yr	based on L'Vovitch, 1954 (river runoff) and on precipitation from Drosdov, 1939
L'Vovich, 1974/ 1979	72,500 km^3/yr	cited by Gleick, 1993; Falkenmark & Chapman 1989; Rogers, 1985
L'Vovich, 1979	71,475 km^3/yr	total land excluding Antarctica, Greenland, and the Canadian archipelago
Lvovitch, 1970	470 mm/yr and 70,250 km^3/yr	water balance estimation of water resources for the whole land
Mather, 1970	69,000 km^3/yr	cited by Baumgartner & Reichel, 1975
Matsuda 1988b	152 mm/yr	European Centre for Medium-range Weather Forecasts (ECMWF)
Matsuda 1988b	260 mm/yr	GFDL
Nijssen *et al*., 2001a	459 mm/yr	based on modelling
Nijssen *et al*., 2001b	483 mm/yr	
NRC, 1986 Shiklomanov, 1997	71,000 km^3/yr	
Oki *et al*., 1995	165 mm/yr	global water balance
Oki, 1999	75,000 km^3/yr	water vapour data by the European Centre for Medium-range Weather Forecasts (ECMWF), data from Korzoun, 1978, and precipitation data from Zie and Arkin, 1996 for 1989-1992
Piexoto & Kettani, 1973	62x10^12 m^3/yr	
Repetto, 1985	72,500 km^3/yr	
Rockstrom *et al*., 1999	70,000 km^3/yr	range: 56,000 to 84,000 km^3/yr; bottom-up estimate
Shiklomanov, 1993	72,000 km^3/yr (485 mm)	
Shiklomanov, 1997	72,000 km^3/yr	World Water Balance and Water Resources of the Earth, 1974
Shiklomanov, 2000c	74,200 km^3/yr	new data set from analysis of world hydrological stations; Estimates terrestrial ET based on "observations" form the world's hydrological network, but he does not explain the exact source of the ET data.
WRI, 1988	63,000-73,000 km^3/yr	compilation of data from several primary and secondary sources

Appendix F. Estimates of Other Variables

Table F1. Clearing rate of shifting cultivation (CR_{sc})

Source	CR_{sc} (original units)	Comments
Vitousek *et al.*, 1986	2050 m^2/capita/yr	average of range of estimate from Seiler & Crutzen, 1980 [ref. 104, p. 217-218], as derived from assembly of other sources
Myers, 1980	0.00143 km^2/capita/yr	from dividing annual conversion of primary and secondary humid tropical forests to agriculture (200,000 km^2/yr) by the number of subsistence agriculturalists in tropical areas (140,000,000)
Palm, Houghton, Melillo, 1986	0.17 ha/capita/yr	for Southeast Asia; includes clearing of both forest and fallow; for 1980
Hall *et al.*, 1985	0.17 ha/capita/yr	1.0 ha/family cleared each year in shifting cultivation, 6 persons per family
Crutzen & Andreae, 1990	0.1-0.3 ha/capita/yr	annual clearing of 20-60 million ha, 200 million people; for 1960s

Table F2. Population that uses shifting agriculture (POP_{sc})

Source	POP_{sc} (persons)	Comments
FAO, 1992	402,200,000	the 1990 resident world population in tropical rainforest areas
Mather, 1990	500,000,000	

Table F3. Density of fibre/construction wood (ρ_w)

Source	ρ_w (original units)	Comments
Vitousek *et al.*, 1986; Armentano & Ralston, 1980	0.6 g/cm^3	assumption
Winjum & Schroeder, 1997	0.52 t/m^3	
Brown & Lugo, 1992	0.69 Mg/m^3	a weighted average wood density calculated from data for two areas of Amazonian forests
Brown, Gillespie, & Lugo, 1989	0.20-1.05 g/cm^3	for tropical forests
Kira & Ogawa, 1971	0.1-0.8 specific gravity	for tropical forests
Birdsey, 1992	0.349-0.758 g/cm^3	for USA; weighted average specific gravity of trees
Sohngen & Sedjo, 2000	400-700 kg/m^3	obtained from a variety of sources published in the 1990s
Brown, 1997, Reyes *et al.*, 1992	0.5-0.8 g/cm^3	wood densities of tree species for tropical regions of three continents
Kauppi, Mielikainen, & Kuusela, 1992; Hakkila, 1989	400 kg/m^3	an aggregate estimate over all species in European forests
Chudnoff, 1984	0.26 to 0.78 specific gravity	calculated from oven dry weight and green volume

continuation of Table F3. Density of construction wood

Churkina & Running, 2000	434 kg/m^3	an average of the wood densities of the most common in the United States' coniferous species; based on Turner et al., 1995
Dean & Baldwin, 1996 Panshin & De Zeeuw, 1970	0.30-0.66 specific gravity	compilation of other sources
FAO, 1985	725 kg/m^3	average wood density for Latin America
Friend *et al.*, 1997	205-305 $kg(C)/m^3$	including bark, based on Cannell, 1984 carbon assumed to be 50% of oven dry weight
Suzuki, 1999	0.40-0.66 g/cm^3	specific gravity for Bornean tropical rainforest trees in early 1990s; mean +/- standard deviation for 353 samples
USDA, 1955	20.8-68.3 pounds / cubic foot	average weights of sawed hardwood and softwood timbers at a moisture content of 8 percent
Woodcock, Dos Santos & Taylor, 2000	0.49 g/cm^3	median value for a tropical hardwood in Australia and Hawaii

Table F4. Volume of forest harvest used for construction and fibre in temperate areas (V_{fhct})

Source	V_{fhct} (original units)	Comments
Bull, Mabee & Scharpenberg, 1998; FAOSTAT	9.9 x 10^8 m^3	industrial wood production for USA, Canada, Europe, former USSR
FAO, 1995	1210 million m^3	for developed countries in 1991 (includes developed Asia and Oceana, Europe, former USSR and North America); for industrial roundwood; green volumes; inside bark volume only

Table F5. Volume of forest harvest for wood used for construction and fibre in tropical areas (V_{fhctr})

Source	V_{fhctr} (original units)	Comments
FAO, 1995	389 million m^3	for developed countries in 1991 (includes developed Asia and Oceana, Europe, former USSR and North America); for industrial roundwood; green volumes; inside bark volume only

Appendix G. Land Cover Data Sets

G1. Agriculture

The map of the present-day distribution of global agricultural lands (Figure G1) was obtained from the University of Wisconsin (Ramankutty and Foley 1998) (archived at SAGE http://www.sage.wisc.edu/download/crop92/croplands.html and ISLSCP II http://islscp2.sesda.com/ISLSCP2_1/html_pages/groups/veg/historic_cropland_xdeg.html), and represents the agricultural land cover of the world on a continuous scale, depicting the percentage of land in cultivation for each 0.5 degree grid cell. This data set was developed to understand the consequences of historical changes in land use and land cover for ecosystem goods and services, and was created by synthesizing remotely-sensed land cover data with contemporary land inventory data.

There are known errors in the inventory data for China, Nigeria, and the Former Soviet Union that are yet to be resolved. Lack of subnational inventory data for the Russian Federation affects the quality of this data set in that region. The presence of extensive cultivation in Patagonia, and strips of cultivation in the Sahara likely reflects misclassifications in the satellite data.

G1a. Irrigated Agriculture

For the map of irrigated areas (Figure G1a), I use a map of the amount of area equipped for irrigation in the 1990's as a percentage of the total area on a raster with a resolution of 5 minutes, produced by Stefan Siebert, Petra Döll, Sebastian Feick and Jippe Hoogeveen (2005) (Global map of irrigated areas version 2.2, Institute of Physical Geography, University of Frankfurt/M., Germany / Food and Agriculture Organization of the United Nations, Rome, Italy (Siebert et al. 2005)).

Version 2.2 of the "Digital Global Map of Irrigated Areas", contains updated maps of Latin-America, Europe, Africa, Oceania and Asia. For these continents the maps were generated on a spatial resolution of 0.01 degree and aggregated to a cell size of 5' (0.0833°, which is about 10 kilometre on the equator). These maps were combined with the 5' map that was generated for the first version of the "Digital global map of irrigated areas". The result is a global map of irrigated areas with a spatial resolution of 5', but the way the map is generated is not uniform. The overall quality of the map depends heavily on the individual quality of the data for the different countries.

For this study, to define whether each 5 minute cell was irrigated or not, I set a threshold of 5% irrigation. This threshold was chosen to preserve the estimated area of irrigation at approximately 17 % of all cropland (Wood et al. 2000).

The irrigated agriculture map produced by Siebert and colleagues (2005) does not show irrigated agriculture in some areas known to have irrigated agriculture; for example: north-east Brazil, lower Volga river where it meets the northern edge of the Caspian sea, and the Orange river basin in South Africa. In addition, I have noted non-irrigated agriculture in barren land / open shrublands in Australia – a situation that is likely a misclassification of either the agricultural or irrigated agriculture rasters because of the improbability of the occurrence of widespread non-irrigated agriculture on arid land.

G2. Built-Up Lands

The map of the present-day distribution of global urban and built-up land (Figure G2) was obtained from the University of Wisconsin (Miteva 2004) (http://www.sage.wisc.edu/atlas/maps.php?datasetid=18&includerelatedlinks=1&dataset=18). This map combines the two main sources of the extent of urban and built up areas: the DMSP/OLS Nighttime Lights (DSMP 2000) and the IGBP land cover characterization data sets (Strahler 2002). Initially the two source data sets were re-gridded to 5 minute resolution. In the newly produced nighttime lights data, each cell represented the average nighttime light value of 4 cells, while each cell in the new land cover data represented the number of cells out of 100 which were categorized in the original IGBP data as "Urban or Built-up land". A linear regression was developed for all non-zero values to establish the relation between the built-up area density, as the dependent variable, and nighttime lights, as the independent variable. The statistics were then applied to the nighttime data set to develop modelled built-up area density. The positive difference to the fractional re-gridded IGBP data set was added to this data set.

G3. Inundated Land (Reservoirs)

There are more than 40,000 large dams worldwide, and up to 800,000 small dams ((WRI) 2000). For the map of present-day distribution of anthropogenic reservoirs (Figure G3) I used a map from University of Kassel (CESR) Global Lakes and Wetlands

Database (WELAREM1) (Lehner and Doll 2004). WELAREM1 is a global ½ minute (~1 km) raster map of wetlands, lakes and reservoirs and was derived by combining various digital maps ((ESRI 1993) - wetlands, lakes and reservoirs; (ESRI 1992) - wetlands, lakes, reservoirs and rivers; (WCMC 1993) - lakes and wetlands; (Vorosmarty et al. 1997) - reservoirs) and attribute data (ICOLD 1998) (Birkett and Mason 1995) - lakes and reservoirs). For the map generation approximately 300,000 vectorized lakes and reservoirs were considered. Wetlands encompass also stretches of large rivers, as it is assumed that only a river with adjacent wetlands (floodplain) is wide enough to be drawn as a polygon on the 1:3 million map of ESRI (1992). In the generated data set, wetlands cover 6.6 % of the global land area (without Antarctica and Greenland), and lakes and reservoirs 2.1 %. The wetland and reservoir data is aggregated from ½ minute dominant land cover to 5 minute percent cover for this study.

G4. Grazing Land

For the map of the present-day distribution of global grazing lands (Figure G4) I used a map from the University of Wisconsin (Ramankutty 2004). Information on the methods used to calculate this map is unavailable. The dataset consists of a five-minute grid with percent cell occupied by grazing land.

G5. Potential Vegetation

Potential vegetation cover, the vegetation cover in present day climate, has been estimated most commonly using biogeography models. For a map of potential vegetation for this study, I chose the widely used dataset (Figure G5) for potential vegetation from the University of Wisconsin (Ramankutty and Foley 1998). It was created by a simulation with the IBIS model to calculate potential vegetation cover, is featured in ISLSCP II and SAGE datasets, and classifies the potential vegetation into IGBP biomes. Because of their importance to the hydrologic cycle, I added wetlands from the WELAREM dataset (Lehner and Doll 2004) to the potential vegetation map.

G6. Wetlands

For the map of wetland areas, I used the global ½ minute (~1 km) raster map of wetlands, lakes and reservoirs WELAREM1 (Lehner and Doll 2004). This map was derived by combining various digital maps (ESRI, 1993 - wetlands, lakes and reservoirs; ESRI, 1992 - wetlands, lakes, reservoirs and rivers; WCMC, 1999 - lakes and wetlands; Vörösmarty et al., 1997 - reservoirs) and attribute data (ICOLD, 1998 - reservoirs; Birkett and Mason, 1995 - lakes and reservoirs). Wetlands encompass also stretches of large rivers, as it is assumed that only a river with adjacent wetlands (floodplain) is wide enough to be drawn as a polygon on the 1:3 million map of ESRI (1992). In the generated data set, wetlands cover 6.6 % of the global land area (without Antarctica and Greenland), and lakes and reservoirs 2.1 %.

To my knowledge, this is the only available map of global wetlands; it is, however, for *present-day* wetlands. Yet it does appear to include several wetlands that no longer exist, for example, it classifies large areas of the Brahmaputra delta as wetlands, when it has now been converted to agriculture, and it includes the southern Iraqi marshes are present on the raster, even though they had been drained; thus, this dataset allows provides a approximation of wetland loss, yet our results likely will be an underestimate.

Notes on GIS Protocol

Mapping analysis was conducted in ESRI ArcGIS9.0. I use the pseudocylindrical equal-area Eckert IV projection for the analysis because the equal area characteristic is necessary for the cell-based ET flux estimates. The global land cover rasters come in a variety of resolutions, from ½ -minute to 0.5 degree. Reservoir and wetland information was gleaned from ½ minute (~1 km) data, and converted into a percentage cover at the 5 minute resolution.

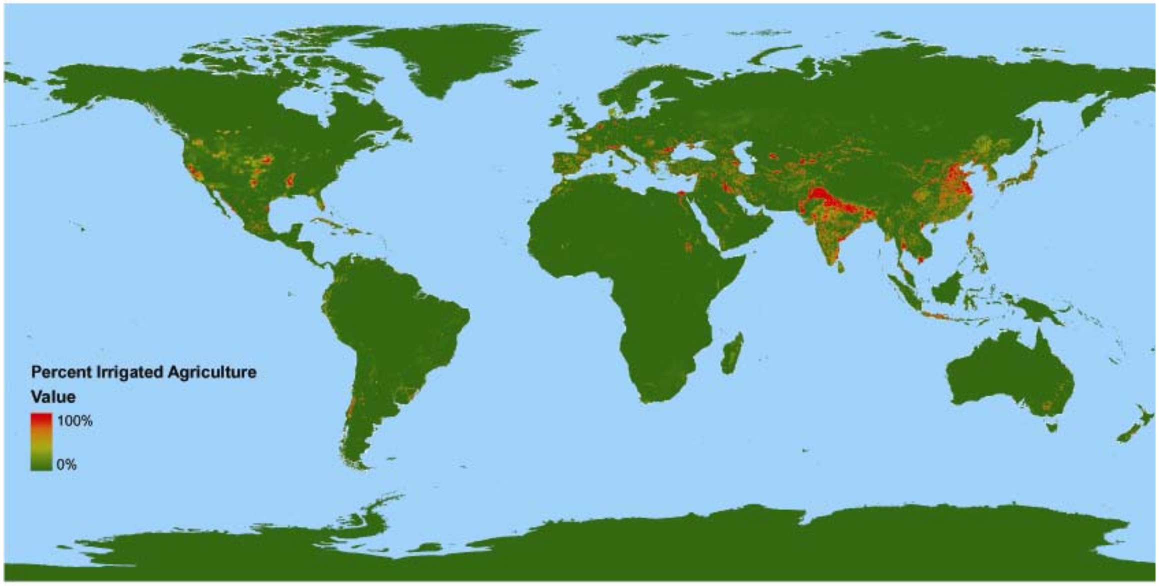


Figure G1a. Global Distribution of Irrigated Agriculture. Original 5 minute resolution. (Siebert et al. 2005)

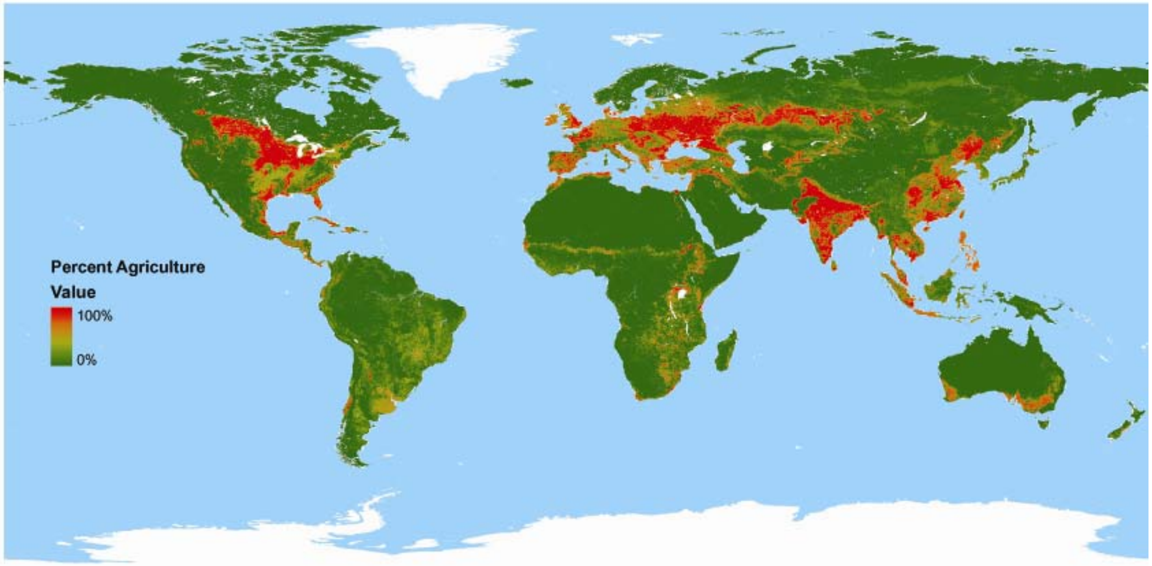


Figure G1b. Global Distribution of Agriculture. Original 5 minute resolution. (Ramankutty and Foley 1999)

Figure G2. Global Distribution of Built-Up Land. Original 5 minute resolution. (Miteva 2004)

Figure G3. Global Distribution of Reservoirs. ½ minute resolution aggregated to 1 degree for visibility (Lehner and Doll 2004)

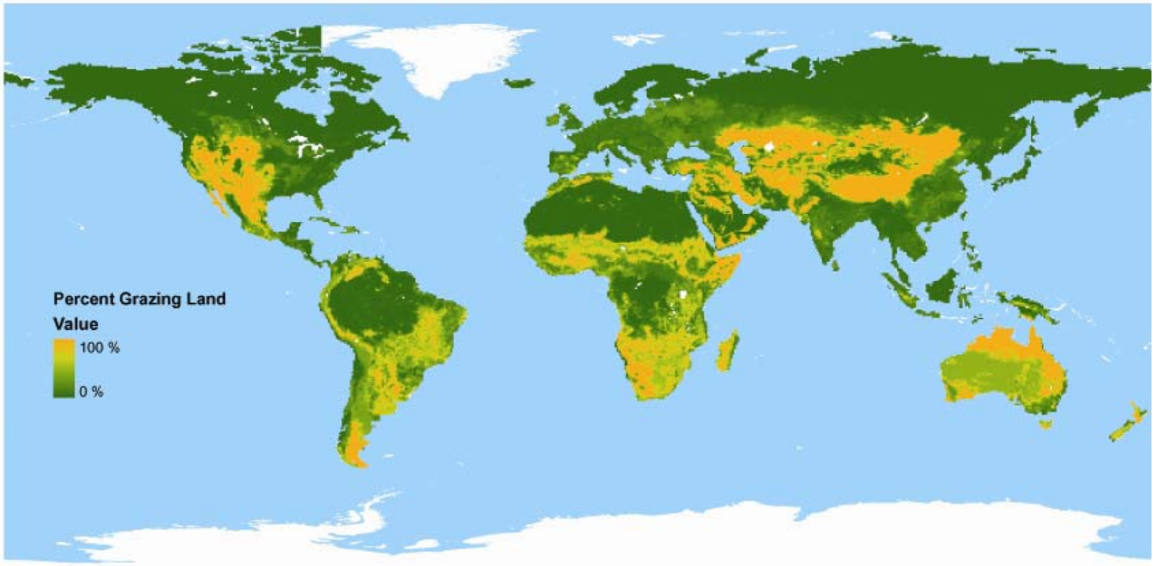


Figure G4. Global Distribution of Grazing Land. Original 5 minute resolution (Ramankutty 2004)

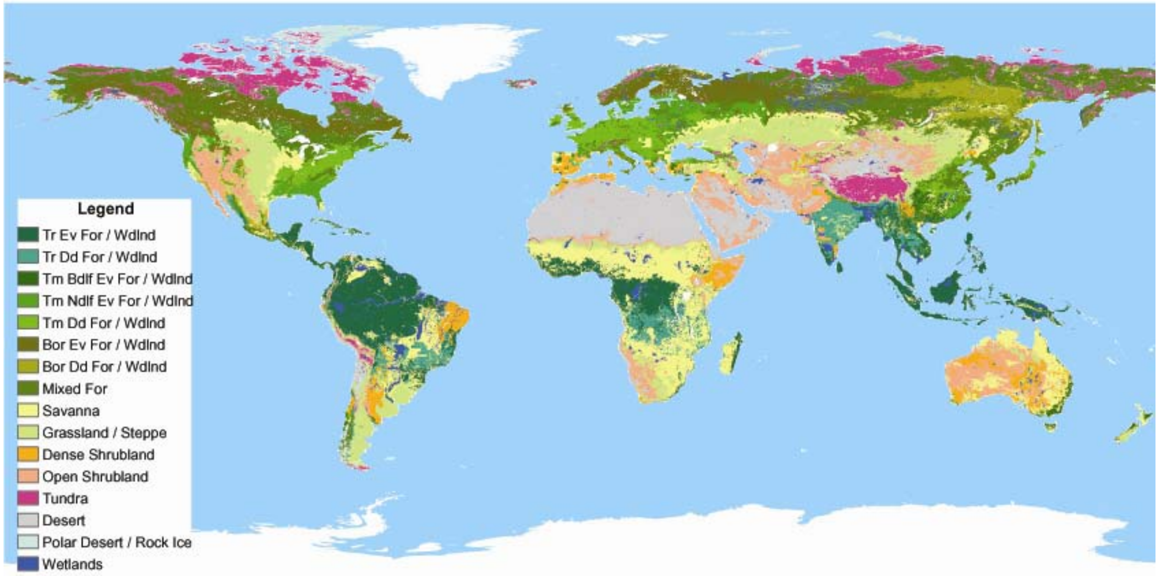


Figure G5. Global Potential Vegetation. Original 5 minute resolution (Ramankutty and Foley 1998), with wetlands added from (Lehner and Doll 2004)

Appendix H. Maps of Kriged ET.

To obtain a global field of ET for each land cover type, the point annual ET data were spatially interpolated using kriging, and a separate kriged field is made for each of the 17 land covers. Ordinary kriging was used, with a spherical model[41], with no transformation or trend removals. The lag size and nugget were chosen based upon observation of the variogram. Twelve lags were used, and lag size used is approximately 10, and nuggets are less than 0.1. Where two or more measurements were made in the same location, the mean of the observations at that location was used for the kriging.

The krigs were checked that they followed global trends in available water and energy by comparison with global climate maps, including precipitation (New et al. 1999), soil moisture (Willmott and Matsuura 2001), potential evapotranspiration, topography (Row et al. 2005), relative humidity (New et al. 1999), and an estimate of global annual ET, not divided into land cover type (Willmott and Matsuura 2001). In cases where the kriged field did not capture areas global trends, estimates of annual actual ET were added, based upon other ET point-estimates from the database from similar land covers in similar climatic (Trewartha 1943), continental, land cover, topographic and latitudinal environments. For the polar boundary conditions, the maximum ET was set to that of potential evapotranspiration (Willmott and Matsuura 2001). Figures H 1-H8 show the annual actual estimated ET (m/yr) for cells in which the given land cover occurs.

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[41] an exponential model was used for evergreen broadleaf forest and grassland because of its better fit with the data as observed on the variogram

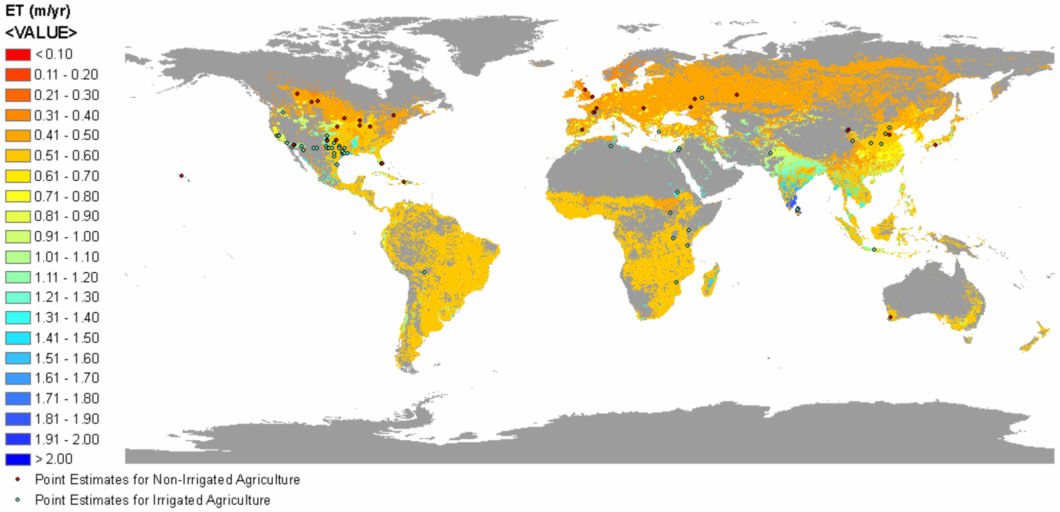

Figure H1. Kriged ET for Agriculture (irrigated and non-irrigated)
5 minute resolution; interpolation from irrigated and non-irrigated agriculture were done separately

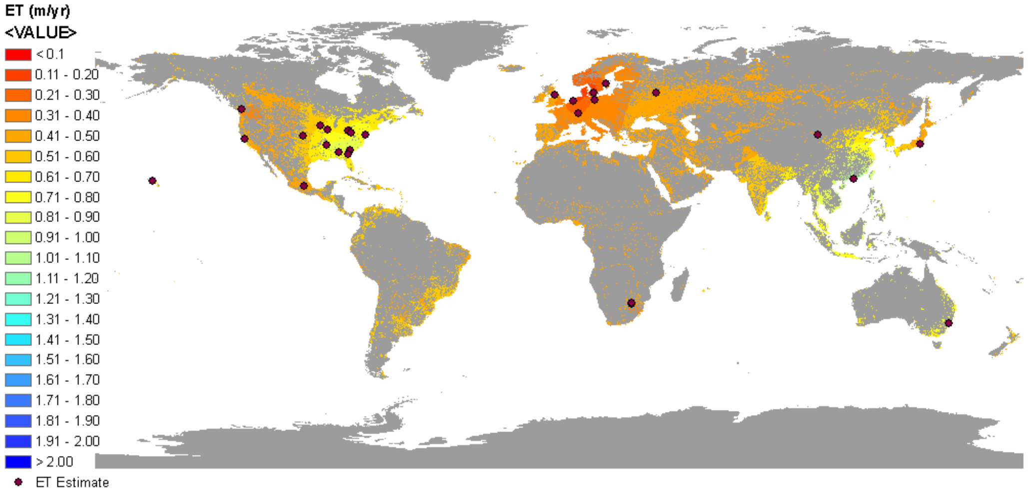

Figure H2. Kriged ET for Built-Up Land.
5 minute resolution

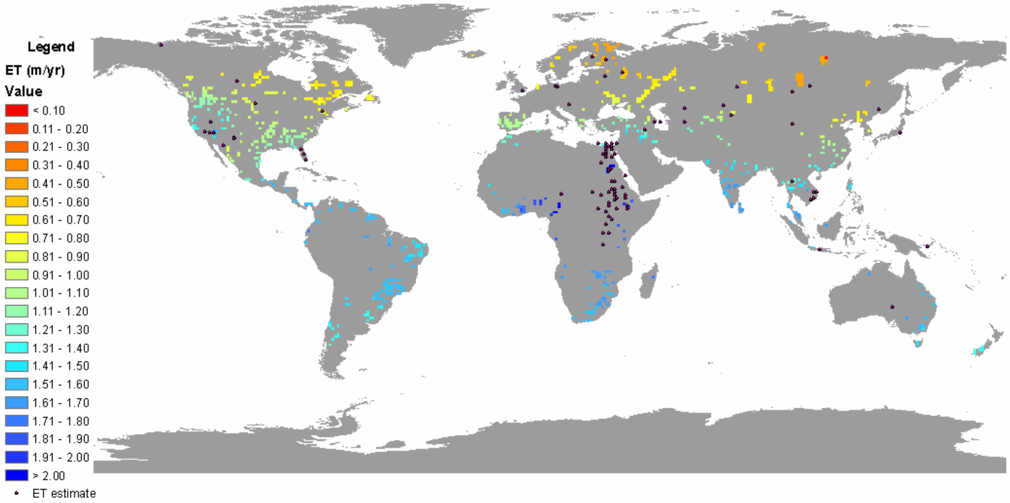

Figure H3. Kriged ET for Reservoirs
5 minute data aggregated to 60 minutes for visualisation

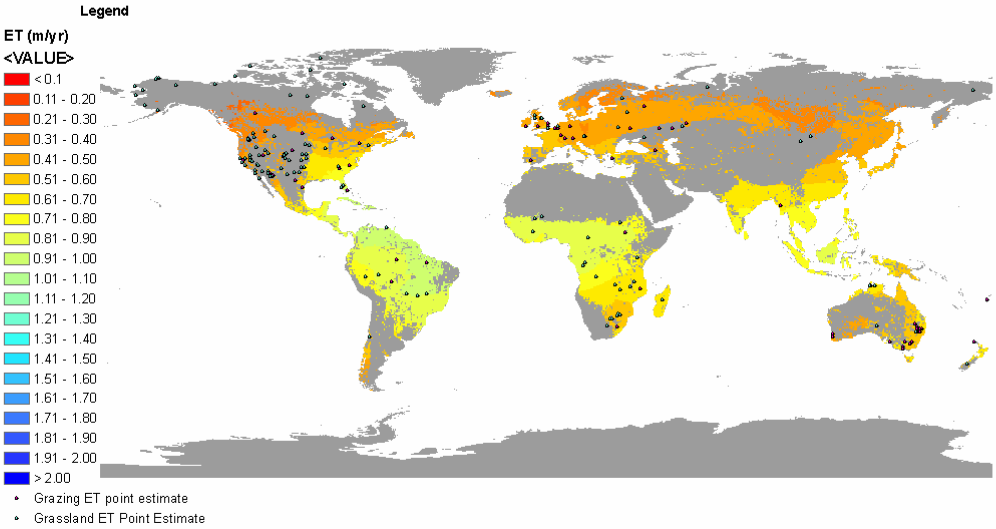

Figure H4. Kriged ET for Grazing Land
0.5 degree resolution. Krig based on both grazing and grassland ET estimates.

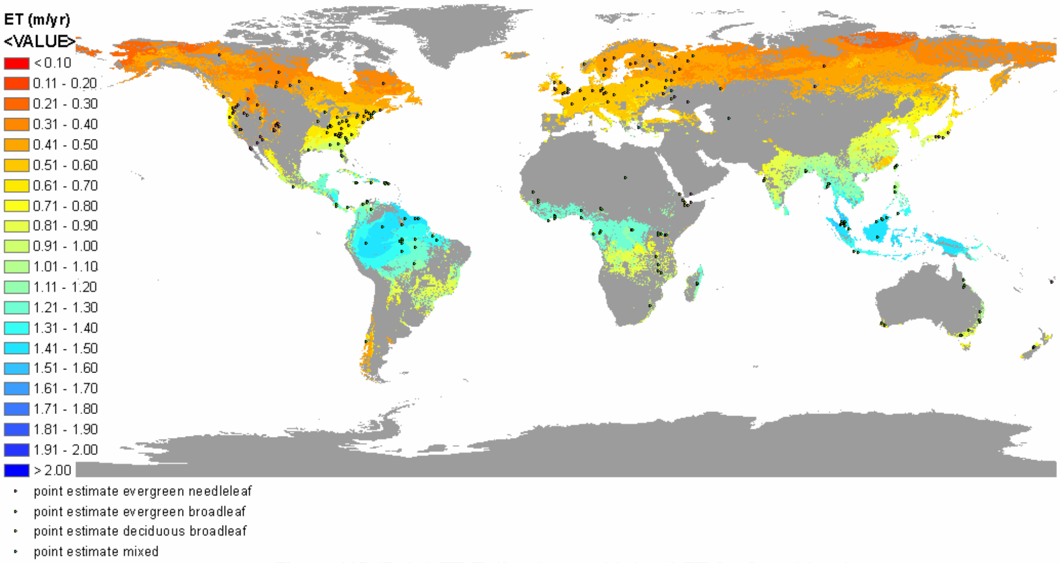

Figure H5. Point ET Estimates and kriged ET for forest land.
5 minute resolution, sub-biomes were kriged separately.

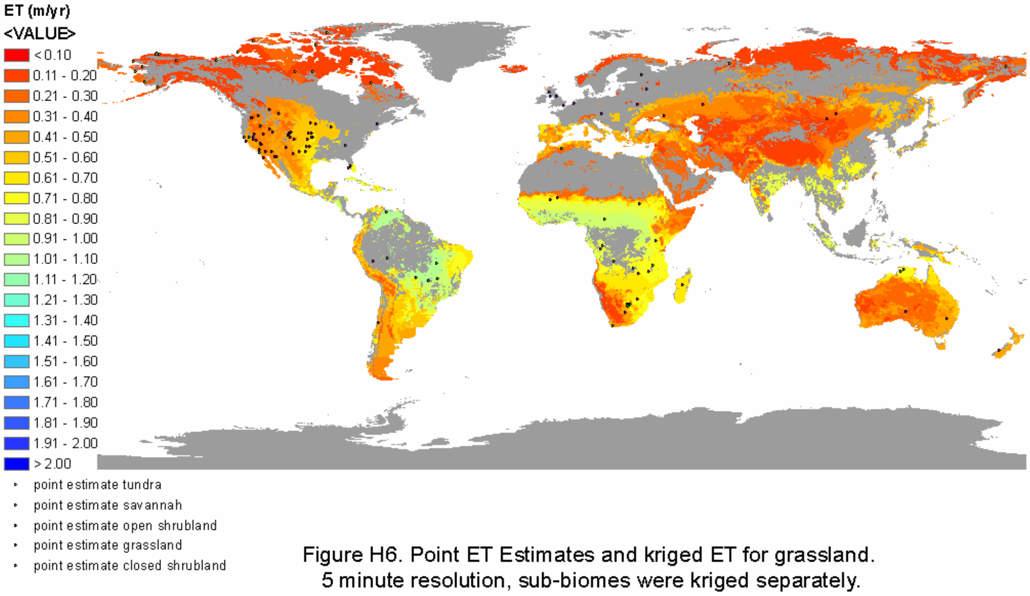

Figure H6. Point ET Estimates and kriged ET for grassland.
5 minute resolution, sub-biomes were kriged separately.

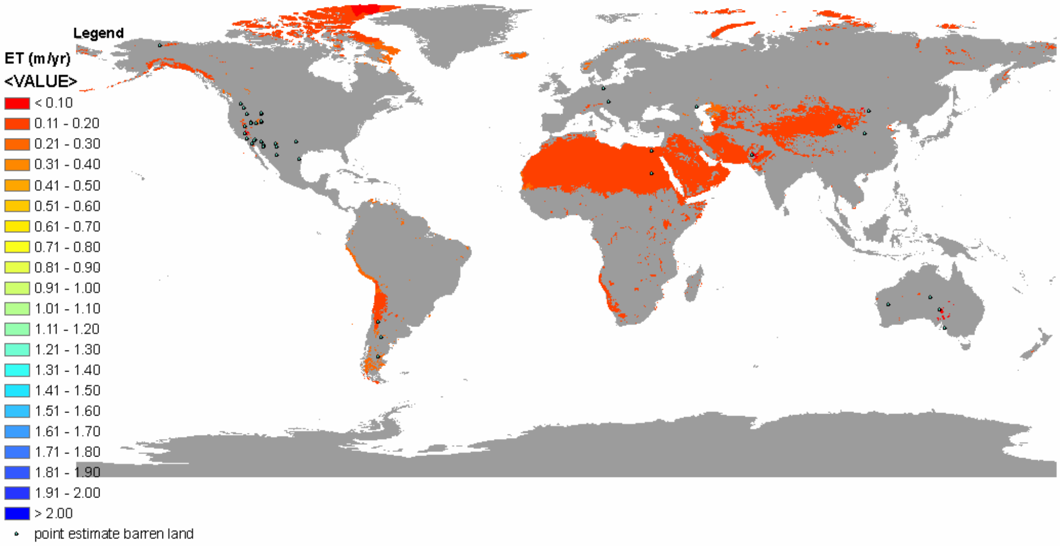

Figure H7. Point ET Estimates and kriged ET for barren land.
5 minute resolution

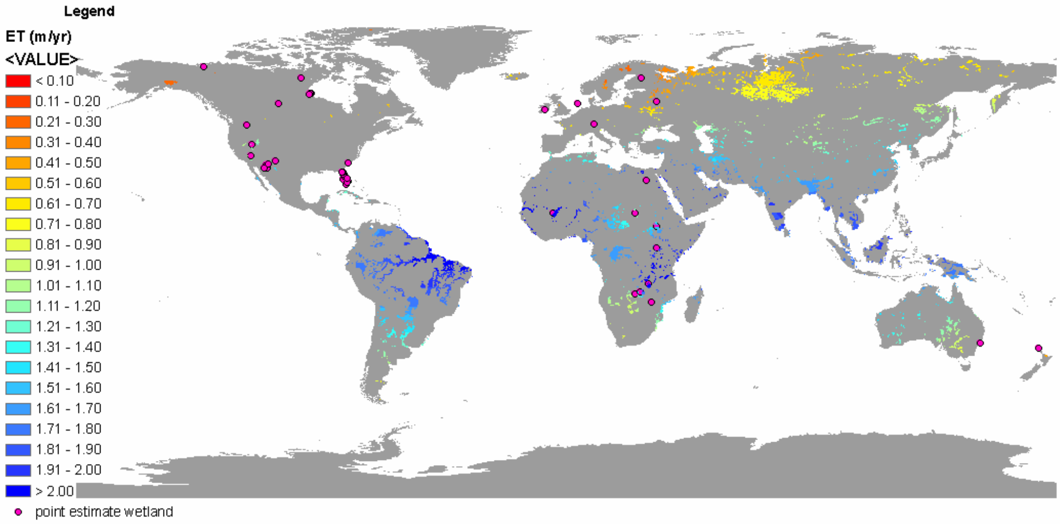

Figure H8. Point ET Estimates and kriged ET for wetlands.
5 minute resolution.

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Biography

Shannon Sterling was born in North Vancouver, British Columbia, Canada on June 30, 1971. She received an Honours Bachelor of Science degree at McGill University, Montreal, Quebec, Canada in 1993, and then continued on to complete a Masters of Science Degree in Geomorphology at the University of British Columbia, Vancouver, Canada in 1997. After working as a consulting geoscientist in British Columbia, Shannon began her doctoral studies at Duke University in 2001.

Shannon has published “Human Appropriation of Photosynthesis Products” in *Science* and “Sediment trapping characteristics of a pit trap and the Helley-Smith sampler in a cobble gravel bed river” in *Water Resources Research*.

Since completing her bachelor degree, Shannon has received the European Union Intra-European Fellowship (2005-2006), the French Government Chateaubriand Fellowship (2004-2005), the Duke University Graduate School award for International Research (2003), Duke University Earth and Ocean Sciences Graduate Student Award (2001-2005), the National Science and Engineering Council of Canada Post-Graduate Scholarship (1993-1994), and the Forestry Canada Post-Graduate Fellowship (1993-1994).