Does Evapotranspiration Increase When Forests are Converted to Grasslands?

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

ΔET_{LCC}	Change in evapotranspiration with land cover change
$\Delta ET_{f\text{-}g}$	Change in evapotranspiration when forests converted to grasslands
BR	Bowen ratio
CWB	Catchment Water Balance
E	Evaporation
EC	Eddy covariance
ET	Evapotranspiration
F-G	Forest to grassland
FGC	Conversion of forests to grasslands
G	Ground heat flux
GFC	Grassland to forest conversion
H	Sensible heat flux
LC	Land cover
LCC	Land cover change
LE	Latent energy flux
LSM	Land surface models
Q	Outflow
P	Precipitation
PET	Potential evapotranspiration
PME	Penman Monteith Equation
RS	Remote sensing
T	Transpiration

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Abstract

Evapotranspiration (ET) plays a critical role in the Earth's water cycle and drives local, regional, and global climates. ET also determines the amount of water input to the surface, driving rates of groundwater percolation, surface runoff and catchment outflow, and therefore determines the water available for ecosystem and human consumption. Because ET rates depend on land cover type, anthropogenic changes such as deforestation, agriculture and urbanization have considerable effects on ET.

The conversion of forests to grasslands (FGC) is a widespread land cover change (LCC) and is also among the most commonly studied changes with respect to its impact on ET; such research employs a variety of experimental approaches, including, paired catchment (PC), Budyko and land surface models (LSM), and measurement methods, including the catchment water balance (CWB), eddy covariance (EC) and remote sensing (RS). Until recently, there has been consensus in the scientific literature that rates of ET decrease when a forest is converted to grassland; however, this consensus has recently come into question. Williams (2012) applied the Budyko framework to a global network of eddy covariance measurements with the results that grasslands have a 9% greater evaporative index than forests. In addition, HadGEM2, a recent Hadley Centre LSM, produced increased ET in the northern Amazon Basin after simulating global scale tropical deforestation (Brovkin et al., 2015). Here I present an analysis of available estimates of how ET rates change with FGC to increase our understanding of the forest – grassland-ET paradigm.

In this study, I used two datasets to investigate the impacts land cover change on ET. I compiled the ΔET_{LCC} dataset using published experiments that compare forest and grassland ET under conditions controlled for meteorological and landscape influences. Using ΔET_{LCC} data, I show that, in all cases, forest ET is higher than grassland under controlled conditions. Results suggest that the eddy covariance method measures smaller changes in ET when forests are converted to grasslands, though more data are needed for this result to be statistically significant. Finally, GETA2.0, a new global dataset of annual ET, shows that forest ET is greater than grassland, except at high latitudes and areas where orography influences precipitation (P). The data included in this study represent the data available on forest and grassland ET comparison and reveal an important gap in the scientific literature: the lack of data available regarding forest to grassland LCC.

Keywords: Evapotranspiration, Land Cover Change, Forest, Grassland, Eddy Covariance, Paired Catchment, Remote Sensing, Water Yield, Water Balance

1.0 Introduction

ET plays a vital role in the Earth's water cycle, supplying ~62% of continental P and affects local, regional and global climates (Dingman, 2002). ET is a critical component of the water budget of a catchment, determining the infiltration to soil moisture and groundwater, surface runoff and catchment outflow, and therefore the water available for ecosystems and human consumption. Because ET rates depend on land cover type (Zhang et al., 2001; Ambrose & Sterling, 2014), anthropogenic changes such as deforestation, agriculture and urbanization have considerable effects on ET. Thus, LCC's have the potential to impact local and regional climates and ecosystems (Yan & Zeng-Hui, 2013).

Implications of LCC on ET are well established, as extensive LCC have modified hydrologic regimes around the globe, including changes in catchment water yield (Bosch & Hewlett, 1982) and salinization of soils (Best et al., 2003), motivating an array of research focused on the impacts of LCC on ET (Bosch & Hewlett 1982; Zhang et al., 2001; Williams et al., 2012). However, ET remains difficult to measure, owing to its nature as a nonlinear vaporous flux from the earth's surface. Additionally, ET is highly sensitive to overlying meteorology and soil moisture, which change rapidly and are spatially variable due to heterogeneities in land cover type, climate, surficial geology and topography. These qualities have compelled researchers to either make generalizations over a catchment or region, or extrapolate small-scale (<100 m) measurements over a larger region in order to estimate ET. The surface water balance (SWB) , where ET is estimated as the difference between incoming P and outflow of a catchment (assuming no changes in storage), is historically the most common method of ET estimation. More recently, the EC method has been used to measure the latent heat flux at a point. RS, which uses satellite-based data to estimate ET, has become more frequently used and provides greater spatial coverage to other methods. In each case, the accuracy of these methods remains limited.

FGC is among the most commonly studied LCC's, dating back to the early 20th century (Hibbert, 1967; Bosch & Hewlett, 1982). FGC studies use an assortment of experimental designs, including before and after deforestation of a catchment, PC, estimated FGC using models from RS data or LSM and global databases containing EC measurements. Until recently, the scientific literature unanimously agreed that rates of ET will decrease when a forest is converted to grassland (Zhang et al. 2001; Bosch & Hewlett, 1982). However, this consensus has recently been questioned by Williams et al. (2012) and Brovkin et al. (2015). My research provides an analysis of data from all available sources of published experiments studying the impacts of FGC on ET rates.

2.0 Background

ET is the sum of E and T of water from vegetated surfaces, bare soils and open water, into the atmosphere (Best et al., 2003). Terrestrial E includes direct evaporation from land surfaces, lakes and rivers, intercepted water in vegetation canopy and litter, moist and saturated soils, and sublimation of ice and snow (Dingman, 2008). T depends on photosynthesis rates in plants, as water vapour passively exits the stomata on leaves and stems, which open to take in carbon dioxide during the daytime. Transpired water originates as soil moisture where it enters through the plants roots. Only ~1 % of this water is consumed during the light-dependant reactions of photosynthesis, while the remaining escapes through the stomata as vapour (Glenn et al., 2007). ET supplies about two-thirds of all terrestrial P and is a principal component in the SWB at the catchment or continental scale (Wang & Dickson, 2012). Additionally, ET is a latent energy flux

(LE) that consumes heat in the phase change from liquid water to vapour and plays a central role in the global energy balance, transferring a global average of 80 W/m^2 of heat energy from the surface to atmosphere (Wang & Dickson, 2012; Trenberth et al., 2009).

2.1 Motivation for studying the impacts of LCC on ET

Changes in land cover from forest to grassland, such as deforestation for timber and pasture lands, are common and have substantial consequences for hydrology and climate on local, regional and global scales (Teuling et al., 2010; Yao et al., 2014). FGC ultimately influences the water yield in a catchment by affecting P rates, stream discharge and groundwater recharge patterns, resulting in increased flood risks (Bradshaw et al., 2007) and even inducing drought at the catchment scale (Aragao, 2012). Changes to LC type have complex consequences for regional and global climate, largely depending on the type, extent of and location of vegetation change (Teuling et al., 2010; Lee & Berbery, 2011; Pontgratz, et al., 2010). ~3% of total global forest area has been lost between 1990 and 2015 (Keenan et al., 2015) and FGC will likely continue as the global population increases (Anon, n.d.), along with the demand for crops and pasture lands (Schmitz et al., 2012). Because FGC has been recognized as a driver for hydrologic and climatic change, it is important that we understand the interactions between forests, grasslands and the climate for short and long-term policy and environmental regulation.

2.2. Drivers of ET with respect to land cover change

Factors affecting ET include overlying meteorology and physiological characteristics of a LC type, and can be classified into four main drivers of ET: atmospheric moisture gradient, available water, available energy, and photosynthesis rates (Sterling et al., 2013).

2.2.1 Atmospheric Moisture Gradient

Changes in LC type will alter the atmospheric moisture gradient by altering the roughness of the land surface (Sterling et al, 2013). The transfer of water from land and plant surfaces to the atmosphere is enhanced by turbulent eddies where winds interact with surface roughness in the boundary layer. Turbulent eddies increase atmospheric conductance of water vapour by drawing the moist air from the surface into the ambient air above, increasing the water vapour gradient and allowing air above the surface to then transmit more water vapour (Brutsaert, 2005). The magnitude of turbulence is determined by wind speed and the size and number of features on the land surface, with taller and more abundant features causing greater surface roughness, leading to greater turbulence. The scale and pattern of changes in LC type also affects the moisture gradient; smaller patches of deforestation (~1 km) increase cloud cover and P, while larger scale (> 200 km) deforestation has the opposite effect (Khanna & Medvigy, 2014).

2.2.2 Available water

Changes in land cover type will alter the land surface regime by changing the root depth of vegetation causing compaction and altering erosion rates, and thus affecting its hydrological properties such as moisture retention, infiltration and runoff (Sterling et al., 2013). The source of transpired water is soil moisture, while evaporation occurs from intercepted rainfall, and pooled or open water (Evaristo et al., 2015). LC changes will alter interception, pooling of water and soil moisture and thus the water available for ET.

2.2.3 Available energy

Changes in land cover type can alter the energy availability by altering the net energy flux available at the land surface (Sterling et al., 2013). Available energy (i.e., net solar shortwave radiation plus net longwave radiation plus changes in storage) provides the main energy source at Earth's surface, which is partitioned into the ground heat flux (G), sensible heat flux (H) and LE. Albedo, a measure how well a land surface reflects shortwave radiation, depends on the vegetation type (Brutsaert, 2005). LC changes alter the energy available for ET by altering albedo and thus the net radiation.

2.2.4 Photosynthesis Rates

Changes in land cover type will alter photosynthesis rates by changing plant species, leaf area, stomatal density, water use efficiency and nutrient availability (Sterling et al., 2013). Photosynthesis rates of a plant determine how much water is taken in at the roots and exits through stomata, and thus supplies T. Photosynthesis rates are affected by climatic factors such as light intensity, nutrient limitations and carbon dioxide concentration and the rates vary depending on plant species (including C3 vs. C4) and size. Plant species with a higher leaf area index, defined as a ratio of a plants one-sided leaf area to ground surface area, or a higher stomatal density, will generally have greater rates of photosynthesis. In addition to photosynthesis, the water-use efficiency, defined as the ratio of CO_2 fixed by a plant to the water lost through stomata, will determine the amount water passing through the plant (Sterling et al., 2013; Brutsaert, 2005).

2.3 ET Measurement and Estimation Methods

Measurement and estimation of ET remains difficult due to variability in overlying meteorology and heterogeneity in land cover. ET can be measured at small scales (from point measurements up to tens of meters) and extrapolated to a larger region; however, extrapolating point-scale measurements to larger regions can lead to biased estimates of ET because of regional heterogeneity of vegetation and climate. Estimation-based methods such as the CWB and RS are more commonly used for catchment and regional scales (Nalger et al., 2005). Following is a brief overview of the more common approaches and experimental designs used to study ET with LCC, and a brief discussion of their respective limitations.

2.3.1 Mass Balance Approach

Water Balance

The water balance is based on the law of conservation of mass and accounts for the inputs, outputs and storage of a hydrologic system. The general water balance can be applied to a soil water profile, catchment or region where P, and outflow (Q) and changes in storage (ΔS) (i.e., soil water & ground water) can be measured or estimated. In the case of catchment and regional water budgets, ΔS is generally assumed to be negligible for periods longer than one year. ET is estimated based on the water balance equation (Equation 1) (Dingman, 2002):

$$ET = P - Q - \Delta S \qquad (1)$$

Catchment Water Balance Method

The CWB provides an estimation of ET at the catchment or regional scale by applying the water balance equation (Eqn. 1) with measurements of water inputs and outputs and changes in storage.

P data are provided through rain gauge measurements, which have good temporal but limited spatial coverage and are often biased; satellite-based measurements, which have better spatial but less temporal coverage; attempts to improve P data have been made recently through merging gauge and satellite measurements (Pan et al., 2010). Q data are provided through catchment outflow gauging stations, which provide less than 10 % uncertainty on a monthly or longer time scale (Wang & Dickson, 2012). Changes in storage of a catchment refers to changes in groundwater and soil moisture which vary with season; however, at an annual or greater scale most studies consider this term to be negligible (Zhang et al., 2001, Senay et al., 2011).

Lysimeters – The Soil Water Balance Method

Lysimeters have been used since the late 19th century to investigate hydrology, plant physiology and crop-soil interactions (Gros & Ehlers, 2009, Wang & Dickson, 2012). Lysimeters consist of a 1 to 20 m^3 soil-filled tank that is buried below the land surface. There are two types of lysimeters used in hydrology: non-weighable and weighable, with the former measuring the amount of water percolating through the soil with a neutron probe and the latter measuring the mass of soil to find the storage changes and drainage. With both designs the soil water balance can be applied to determine ET (Wang & Dickson, 2012). Tereno, a hydrologic research group in Germany, have recently developed a network of lysimeters (SoilCan) to study the effects of land use and climate change on terrestrial hydrology (Putz et al., n.d.; Gebler et al., 2015)

Experimental Designs for LCC - Paired catchments

PC studies use two adjacent catchments with similar physical and biological characteristics such as vegetation, climate, area, slope, aspect, soils and bedrock geology. The catchments are monitored for all components of the water balance over a calibration period and then one of the catchments is modified while the other remains as a control. Treatment applied to the catchment is most often afforestation, deforestation, regrowth or conversion of forest type. After treatment, both catchments are monitored for a number of years and any changes of water yield, or outflow, can be related to changes in evapotranspiration through the water balance equation (Best et al., 2003).

The PC approach has been used since the early 20th century to investigate the effects of LCC on catchment water yield. The 1911 study at Wagon Wheel Gap, Colorado is recognized as the first to use two similar catchments, with a "treatment" applied to one while using the other as a control. The catchments were first monitored for eight years and then vegetation was cleared on one catchment, with streamflow measurements then monitored on both catchments for the next 7 years. Results for this study showed that clearing vegetation from a catchment increased streamflow and that effects of land cover change on water yield could effectively be assessed (Hibbert, 1967).

Limitations and Uncertainties

While the SWB applied with a PC design has historically been used to determine changes in ET with LCC, assumptions made in applying the SWB create some degree of uncertainty. Difficulty in obtaining accurate regional scale values from point measurements of P has been improved by using satellite data and radar; however, outflow and changes in soil moisture and groundwater storage remain subject to errors due to our inability to directly measure groundwater and deep soil moisture amounts (Wilson et al., 2001; Best et al., 2003). Additionally, many experiments report results based on short-term experiments (within five years after treatment), when hydrologic equilibrium and maximum changes in water yield may not occur until five or more years post-treatment (Vertessy, 1999). Furthermore, catchments used in these experiments are typically quite small (catchments used in Zhang et al. (1999) had a mean size of 1.25 km^2); large catchment experiments, where treatment is applied to patches of a catchment, may produce less dramatic water yield changes (Munday et al., 2001; Wilk et al., 2001), so upscaling of smaller catchment results may not be accurate (Best et al., 2003). In sum, the main limitations are obtaining accurate and long term P, outflow, changes in soil moisture and groundwater storage data as well as upscaling small catchment results to regional or global scales.

2.3.2 Energy Balance Approach

Surface Energy Balance

The primary contribution to the surface energy balance is incoming shortwave solar radiation, over half of which (~52%) is reflected by the clouds or absorbed by the atmosphere. The remaining radiation is absorbed into earth's surface (net radiation, R_n) and is partitioned into the ground heat flux (G), sensible heat flux (heat energy from Earth's surface to atmosphere, H) and latent heat flux (evapotranspiration, LE). Components of the energy balance can be represented by the simplified surface energy balance equation (Equation 2), where LE, can be calculated as the residual (Wang & Dickson, 2012).

$$\mathrm{LE} = R_n - S - G \qquad (2)$$

Bowen Ratio Method

The Bowen Ratio (BR), defined as the ratio of sensible and latent heat fluxes, can be employed to estimate ET at a point, using ground-based meteorological measurements of air temperature and vapour pressure taken at a minimum of two different heights above a canopy (Tomlinson, 1994). This ratio can then be combined with measurements of net radiation and G and used in conjunction with the energy balance equation to determine ET (Wang & Dickson, 2012).

Limitations and Uncertainties

While the Bowen Ratio is commonly used in homogeneous grassland and agricultural sites, it is not considered suitable for areas of greater surface roughness. This is due to its need for heat and water vapour coefficients to be assumed identical and temperature and humidity measurements to occur within the constant-flux layer in the overlying atmosphere. Thus the Bowen Ratio does not work in highly stable or unstable conditions such as forests which tend to have a higher surface roughness (Wang & Dickson, 2012).

2.3.3 Mass Transfer Approach

Eddy Covariance Method

The eddy covariance approach uses towers fitted with micrometeorological sensors at multiple heights that estimate CO_2, latent heat and sensible heat fluxes from measurements in the atmospheric boundary layer. Three-dimensional sonic anemometers are used to measure wind speed and temperature, and fast-responding oxygen sensors measure water vapour and CO_2 while scalar concentration fluctuations of water vapour, temperature and CO_2 are measured using open- and closed- path infrared gas analyzers (Baldocchi et al., 2001). Data from these measurements are statistically analyzed using co-variances of three-dimensional changes in concentrations, allowing for the computation of latent and sensible heat fluxes. Results can then be validated using the surface energy balance by obtaining data from a net radiometer (net radiation) and soil flux plates (G) (Eugster & Merbold, 2015).

Experimental Designs for LCC - Eddy Covariance Networks

EC first emerged in the 1960's and has since expanded to networks of EC flux towers, with over 650 sites, that monitor carbon and water exchanges on various LC types and in different climatic conditions around the globe (Baldocchi & Ma, 2013; Anon, n.d.). Studies looking at the effects of different land cover types on ET are conducted with EC towers measuring fluxes on plots of land representing LC types of interest. LCC research using EC is conducted by either using a statistical means to compare geographically and climatically dissimilar plots of land (Williams et al., 2012, Sterling et al., 2014), or using adjacent plots or plots within a smaller geographical region (e.g., large catchment) that are thought to have minimal climatic differences (Wolf et al., 2011; Stoy, 2006; Baldocchi & Ma, 2013).

Limitations and Uncertainties

There has been substantial discussion in the literature regarding uncertainty in EC measurements, specifically the inability of EC to close the energy balance and the need to gap-fill data. Wilson (2002) evaluated 22 FLUXNET sites using the energy balance ratio and found a mean imbalance of ~20%, with lower turbulent fluxes providing greater imbalance. Franssen et al. (2010) studied the energy balance closure of EC and found that both highly turbulent and highly stable conditions caused deficits in energy balance closure.

Novick et al. (2009) studied nocturnal evaporation (ET_n) in an old field, pine plantation and hardwood forest and found that, contrary to long-held beliefs that transpiration shuts down at night with closure of stomata, a significant amount (8-9 %of daily ET) transpiration actually occurs overnight, with ET_n of forests being dominated by transpiration, while ET_n of grasslands predominately evaporation. They concluded that weak turbulent fluxes from nocturnal ET are not being properly accounted for, and any gap-filling of EC data must take this into consideration (Novick et al., 2009).

Several methods of have been devised to close the energy balance, such as preserving the Bowen Ratio (Twine et al., 2000) using the Penman-Monteith equation (Stoy, 2006) or averaging the flux measurements over a longer time period (than 30 minutes) (Leuning et al., 2012, Chen & Li, 2012). However, results from these methods appear to vary, with Baldocchi & Ma (2013) and Stoy (2006) obtaining accurate estimations of ET, while Scott (2010) and Imukova et al., (2016) found ET was overestimated by 9-14% and 24-48% respectively.

2.3.4 Combined Methods Approach

Penman Monteith and Priestley-Taylor Equations

The Penman Monteith equation (PME) (Figure 2.1) enables the estimation of ET for a uniform surface (vegetation, bare soil) using meteorological measurements of temperature, humidity, wind speed and surface radiation as well as a coefficient for canopy resistance and aerodynamic resistance, based on LC type (Wang & Dickson, 2012). The PME is commonly used in conjunction with RS data and LSM to obtain estimated ET. It is also used in calculating potential ET (PET), or the ET that would occur with an unlimited water supply, and reference ET, or the rate of ET from a hypothetical reference crop (Irmak et al, 2011.). A simplified form of the PME was developed by Priestley & Taylor (1972) who found that in areas of low moisture stress, the aerodynamic terms could be considered a constant, and thus replaced these terms with the "Priestley-Taylor parameter" (Wang & Dickson, 2012).

$$ET_{sz} = \frac{\frac{1}{\lambda \rho_w}\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (1)$$

(R_n) is the net radiation
(G) is the soil heat flux
(T) is the daily average temperature
(u_2) is the daily average wind speed
(e_s) is the saturation vapor pressure
(e_a) is the mean actual vapor pressure
(Δ) is the slope of the saturation vapor pressure-temperatur curve
(γ) is the psychometric constant
(C_n) and (C_d) are constanst based on crop reference type and simulation time step
(λ) is the latent heat of vaporization
(ρ_w) is water density

Figure 2.1. Penman Monteith equation for evapotranspiration. From Cuashi (Anon, n.d.)

Remote Sensing Method

ET can be estimated over short or long time scales at spatial scales ranging from local (10 m) to regional and global scales using RS measurements. Satellite data from optical and thermal infrared radiometers are able to capture soil moisture, air temperature, land-surface temperature and humidity. Spatial and temporal soil moisture and vegetation characteristics such as leaf area index, surface albedo and emissivity can also be remotely sensed and used as parameters in RS models (Martens et al., 2015; Liou & Kar, 2014, Glenn & Heute, 2007). Additionally, optical measurements of canopy colour can be used to determine a Normalized Difference Vegetation Index, which can be used as a parameter in surface energy balance models and also used alongside meteorological data from the surface to directly estimate ET (Glenn & Heute, 2007). These satellite and meteorological data can then be used as inputs to complete the surface energy balance or used in the Priestly-Taylor or Penman-Monteith equations to obtain estimations of ET (Wang & Dickson, 2012).

Experimental Designs for LCC - Remote sensing

RS methods have been in use since the 1970's and, as with EC methods, rapid developments in technology and infrastructure have improved remote sensing capabilities, and thus allowed for better ET modelling (Nouri et al., 2013). Models are created to estimate the effects of LC change on ET using remotely sensed data observed from the areas or plots of land cover being compared. These are divided up into grid cells, based on the resolution of the satellite, and energy balance and vegetation data are collected for each cell. Collected data are then used to compute ET based on parameterized vegetation classes and most commonly the surface energy balance or PME, providing ET estimates by land cover type. RS is applied in studies from small plots to catchment and global scales (Zhao & Jackson, 2014, Nosetto et al., 2005, Miralles et al, 2011). Some studies use the existing land cover in the study area and apply parameters of different vegetation types to the model to compute LCC effects of ET (Dunn & Mackay, 1995), while others compare deforested, afforested or regrowth plots (Nosetto et al., 2005, Zhao & Jackson, 2014).

Limitations and Uncertainties

RS data provide better spatial coverage and are more cost effective than other methods of estimating or measuring ET (Nouri et al., 2013); however, RS estimations of ET contain inherent uncertainties due to acquisition of satellite and ground based data as well as the algorithms used to compute ET. Remotely sensed data can only be acquired at a defined frequency which depends on the satellite being used. For example, LANDSAT has a 16-day overpass return time, which limits data acquisition to once every 16 days. Allen (2010) found this 16-day return time to be insufficient to produce annual estimations of ET, as clouds frequently inhibit the collection of RS data. Additionally, RS estimations depend on ground-based meteorological measurements to calibrate and correct biases in satellite-obtained surface energy balance components (such as atmospheric correction, albedo and net radiation) and the fusion of additional satellites to provide gap-filling data (Wang & Dickson, 2012, Irmak et al., 2011, Cammalleri et al., 2014). Several other limitations and biases affecting ET estimations have been discussed in the literature including the neglect of forest canopy interception loss (Jimenez et al, 2011), the inability to measure nocturnal ET (Liou & Kar, 2014) and the inconsistency among RS algorithms used to estimate ET (Zhang et al., 2015; Liou & Kar, 2014).

Land Surface and Global Hydrologic Models

Land Surface Models (LSM) use numerical modelling based on a number of methods, including Monin-Obukhov Similarity Theory (Monin & Obukhov, 1954), which describes turbulent mixing in the surface layer of the atmosphere, as well as the Penman-Monteith and Priesltey-Taylor equations, which simulate climatic and atmospheric conditions (Mueller et al., 2013).

LSMs are driven by meteorological forcings such as incoming and outgoing radiation, P, winds, humidity, temperature and atmospheric pressure that are obtained from atmospheric forcing datasets or coupled with atmospheric models (Wang & Dickson, 2012). LSM's model ET for different land cover types using parameters to represent the differences in physical and biological processes for each LC type (Sud et al., 1990, Wang & Dickson, 2012).

Experimental Designs for LCC - Land Surface Models

LSMs have been used to estimate ET with LCC since the 1980's and are commonly used in simulations of Amazonian deforestation. In these simulations, LC types, including forests, grasslands, and deforestation are parameterized based on biological and physical characteristics such as albedo, soils, photosynthesis rates and atmospheric diffusion. These parameters are run through the LSM simulation at regional to global scales and ET rates for each LC type are observed (Famiglietti & Wood, 1991, Dickson & Henderson-Sellers, 1988). These experiments are also employed in a control-treatment design as well as observing changes in LC over time (Sterling et al., 2013; Piao et al., 2007).

Limitations and Uncertainties

LSM's, like remotely sensed ET estimations, have good spatial coverage (either regional or global ET models) but have limitations. LSMs use point-scale ground measurements, forcing datasets or coupling to atmospheric models to provide parameter inputs. Ground measurements, which are usually short-term observations and are subject to uncertainty themselves, are then up-scaled to large resolution (10+ m), three dimensional grids that can create biased parameter coefficients (Wang & Dickson, 2012). Furthermore, land surface parameters used in LSMs do not effectively translate plant functional types (PFT), which are important to differentiate in hydrologic studies as PFTs differ in transpiration rates and water use efficiency (e.g. C3 vs. C4 photosynthesis) (Sterling et al., 2013). Finally, large discrepancies have been found in how LSMs partition temperature and evaporation (Dirmeyer et al., 1999), significantly influencing how LSMs quantify ET with LCC (Lawrence & Chase, 2009). These examples of bias in LSMs are just a few of many discussed in the literature (Wang & Dickson, 2012). Recent development of multi-year in-situ or satellite-based forcing datasets have been employed in an attempt to reduce some uncertainty and bias in LSM ET products (Mueller et al., 2013).

2.3.5 The Budyko Framework

The Budyko framework (Budyko, 1974) estimates the evaporative index (ET/P) as a function of the dryness index (PET/P) (Figure 2.2). The framework provides a supply-demand model that allows for the comparison of locations around the world by accounting for energy balance and water balance controls on ET, and has been used in conjunction with numerous ET estimation and measurement methods including WB (Zhang et al., 2001) and EC (Williams et al., 2012). In the Budyko framework, the evaporative index (ET/P) is plotted against the dryness index (PET/P). The Budyko curve is plotted as a prediction of where evaporative indices should be as a function of aridity indices, with the “demand limit” occurring where ET=PET and the “supply limit” occurring where ET=P (Gerrits et al., 2009). In general, humid climates will plot on the energy-limited area while arid climates plot on the water-limited area. Departures from this predicted curve are partially controlled by vegetation type and thus this plot can theoretically be used to compare LC in different climates. A major assumption with this framework is that the area of measurement is in steady-state, meaning that there are no changes in storage at the spatial or annual temporal scale (Williams et al., 2012).

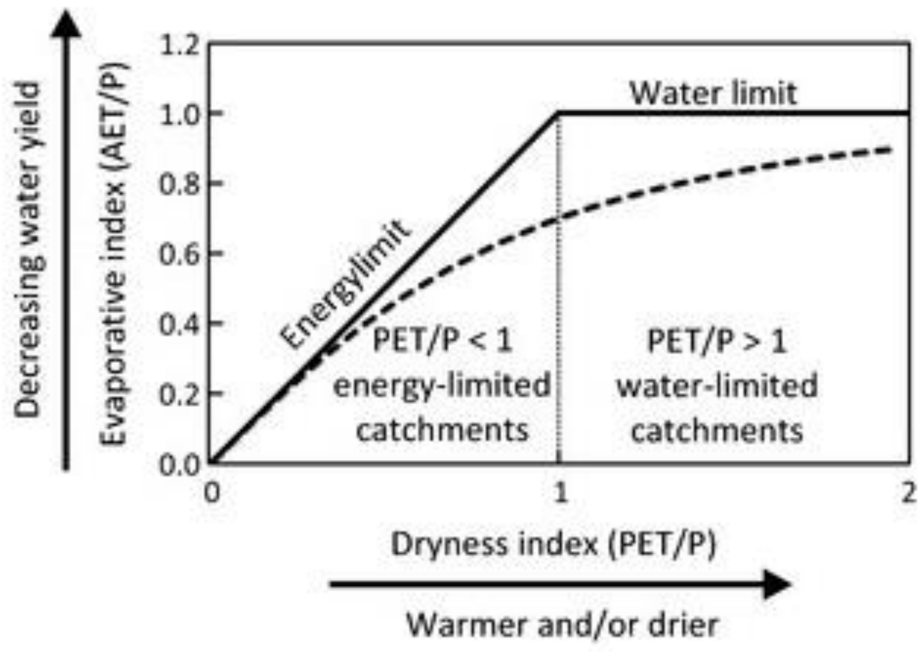

Figure 2.2. The Budyko Curve. From Creed & Xao (n.d.).

2.4 Literature Review

2.4.1 Historical Experiments

The first experiments looking at the effects of LCC on water yield occurred in the early 1900's when Swiss scientists studied two small catchments in the Emmenthal Mountains – one catchment completely forested and the other pastureland. Streamflow, P and climate were monitored and attempts were made to determine the influence of forests on the water budget, but there were no watershed controls used so evidently no links of streamflow to forest cover could be made with any certainty. The PC approach emerged with the Wagon Wheel Gap study in

1911 and was followed by studies in the US by the US Forest Service and in South Africa through the 1930 to 1950's (Hibbert, 1967).

In 1967, Alden Hibbert compiled 39 studies completed between 1911-1964, looking at the monthly effects of changing forest cover on water yield. Using studies from research catchments and experimental forests across the United States as well as Africa and Japan, Hibbert compared results from these studies and came to three general conclusions: "Reduction of forest cover increases water yield, establishment of forest cover on sparsely vegetated land decreases water yield and response to treatment is highly variable and for the most part unpredictable" (Hibbert, 1967). Bosch and Hewlett (1982) built upon the Hibbert study by adding an additional 55 PC experiments and concluded that they had enough statistical evidence to disprove Hibbert's third conclusion and claim that forest response to treatment can be predicted with "fair accuracy" (Bosch & Hewlett, 1982).

Throughout the 1980's, land surface models were developed with the goal of investigating effects of tropical deforestation. Studies by Henderson-Sellers & Gornitz (1984), Dickson & Henderson-Sellers (1988), Sud, Sellers & Mintz (1989), Lean and Warrilow (1989), Gordon et al. (2005), Piao et al. (2007), and several others all employed LSM's to simulate changes in ET and the hydrologic cycle. General consensus with all studies described decreases in ET and P and changes in albedo and the surface energy balance.

As computing and satellite technology improved towards the end of the 20th century, EC and RS became a more feasible and effective means of measuring and estimating ET. RS emerged in the 1990's, providing superior spatial coverage to other "point" methods of estimating ET. Using RS, researchers could now develop parameters for LC types and model LCC with data collected remotely; this allowed the study of LCC as well as mixed vegetation ET in all areas of the Earth at global (Choudhury & Digirolamo, 1998, Yuan et al., 2010), regional (Liu et al., 2007, Fang et al., 2015) and catchment scales (Nosetto et al., 2005). Remotely sensed data has also been used in conjunction with LSM's to investigate the impacts of land cover change on ET at a regional scale (Dunn and Mackay, 1995, Thomas, 2008).

Micrometeorological measurements first emerged in the 1950's and were primarily used in measuring ET and CO_2 fluxes over short vegetation such as grasses and agricultural fields. However, early EC instrumentation and theoretical understanding of turbulent water and carbon fluxes in the boundary layer were not sufficient to accurately measure ET over forests until the 1980's. By this time, instrumentation such as sonic anemometry, infrared spectrometry and digital computing, as well as a better understanding of how turbulent mixing above forests affected vertical vapour gradients, had developed, allowing the first experiments measuring ET over forests (Baldocchi et al., 2013). Experiments by Sellers et al (1995) and Gash et al (1997) were among the first EC studies looking at water and carbon fluxes over complex landscapes of the Boreal forests (Sellers, 1995) and the Sahel (Gash et al., 1997). A rapid expansion of EC ensued, and a global network of eddy covariance flux towers was created through 1990's, allowing researchers to monitor vapour and CO_2 fluxes of various of LC types in a range of climates and geographical areas (Baldocchi et al., 2001).

Throughout the 1990's and 2000's, many EC studies comparing forest and grassland ET were published, primarily comparing geographically distant sites exposed to differing climates (Ponton et al., 2006, Yu et al., 2006), although a few EC studies have since focused on comparing nearby or adjacent plots of forests and grasslands (Stoy, 2006, Dore et al., 2012, Baldocchi & Ma, 2013). Contributions to the FLUXNET dataset expanded quickly in recent times allowing the comparison of dozens (Wilson et al., 2002) to hundreds (Williams et al., 2012) of sites representing natural and anthropogenic LC types.

The CWB remained commonly used method to investigate the effects of LCC on ET through the turn of the century. Following the work of Hibbert (1967) and Bosch & Hewlett (1982), Zhang et al. (2001) compiled results from more than 250 catchments worldwide to investigate the response of annual ET to changes in vegetation. Zhang et al. (2001) determined statistically that the most important factors affecting ET rates were annual rainfall, PET and vegetation type. Zhang et al. (2001) plotted the data in Budyko space and in ET vs. P plots and concluded that forested catchments generally had greater annual ET than non-forested catchments, with a greater difference in high-rainfall areas (Zhang et al., 2001). Farley et al. (2005) assembled a similar study (504 observations) looking at the effects of afforestation on ET and found that annual runoff reduced by 44% when grasslands and shrublands were afforested (Farley et al., 2005). Numerous other individual studies have been completed comparing forest and grassland ET in paired catchments with results that unanimously support the notion that forests have greater ET than grasslands (Hudson et al., 1997, Jipp et al., 1998, Marc & Robinson, 2007, Adelana et al., 2015).

With nearly 100 years of forest LCC studies have showing that forest ET is greater than grasslands, recent developments put the scientific literature consensus into question. Williams et al. (2012) synthesized data from 167 EC sites worldwide to investigate climate and vegetation controls on ET. A variety of land cover types were represented in the data and Williams et al. (2012) used the Budyko framework as a means to normalize the observations. Plotted in Budyko space, the results of Williams et al. (2012) present opposing data about forest and grassland ET. Williams et al. (2012) found that grasslands had a 9% greater evaporative index (ET/P) than forests, pointing specifically towards deciduous broadleaf and evergreen needle leaf forests as having lower ET than grasslands. In addition to Williams et al. (2012) findings, the Hadley Centre Global Environmental Model, version 2 (HadGEM2), simulated the impacts of tropical deforestation on ET and found an increase of ET would occur in the northern Amazon Basin, while temperatures would decrease (Brovkin et al., 2015).

2.4.2 Comparison Studies

A number of more recent studies have focused on comparing point measurement methods of ET with larger scale methods such as WB or RS, and have obtained inconsistent results. Wilson et al (2002) compared EC and WB of a forested catchment over a 5-year period and found they produced ET that agreed within 2%. Kosugi & Katsuyama (2007) compared EC and WB in a Japanese cypress forest and found that they produced similar ET, but only after closure was forced on the energy balance for EC. Scott (2010) compared WB and EC in semiarid ecosystems and found that forcing the energy balance closure actually produced poorer results between the EC and WB methods. Michel et al. (2016), Zhang et al. (2015) and Miralles et al. (2011) compared RS to FLUNXET data over a range of LC types. Miralles et al (2011) found a strong correlation (R = 0.8) between the two methods, while results from Michel et al (2016) showed a moderate to strong agreement (R^2 = 0.58-0.77) and Zhang et al. (2015) found a 30% disagreement of forest ET between RS and EC. Inconsistent results from these comparison studies highlight the current uncertainty in scientific research regarding ET.

2.5 Knowledge gaps

The scientific literature shows that, even though there is a substantial amount of research investigating the effects of F-G LCC on ET, uncertainty still exists, and further analyses are required to improve our understanding. Recent work by Williams et al. (2012) and Brovkin et al. (2015) have placed previously-held notions of forests having higher ET than grasslands into doubt. There are numerous studies comparing syntheses of F-G ET using individual LCC methods (Bosch & Hewlitt, 1982, Zhang, 2001, Williams, 2012) and comparing ET by LC type with multiple measurement types, but a synthesis of F-G ET using several measurement and estimation methods is absent in the literature and needed to improve our understanding on how F-G LCC affects ET. In addition, there are many models using LSM, RS and statistic models to simulate the effects of tropical deforestation on global ET (Brovkin et al., 2015), or estimating global ET by LC type (Miralles et al., 2011; Kim et al., 2012; Muller et al., 2013, Ambrose & Sterling, 2014), but a global ET dataset has not yet been used to compute ET with a global FGC. Thus, a FGC analysis would help to highlight where forests may have higher ET than grasslands.

2.6 Research questions and objectives

With the broader goal to address the controversy arising from Williams et al. (2012) and Brovkin et al., (2015), my objective is to summarize available sources of knowledge regarding how ET is affected by F-G LCC, and to determine whether the measurement or estimation methods used affect the forest and grassland ET results.

My research questions and hypotheses are:

RQ1. Is $\Delta ET_{f\text{-}g}$ always negative when natural forests are converted to grasslands?

RQ1a. Are there any instances in the literature where there is an increase in ET when forests are converted to grasslands?

H1: ΔET is always negative when natural forests are converted to grasslands.

H1a. There are no instances in the literature where there is an increase in ET when forests are converted to grasslands.

RQ2. Does the literature show that $\Delta ET_{f\text{-}g}$ varies with ET measurement/estimation method?

H2: The literature does show that $\Delta ET_{f\text{-}g}$ varies with ET measurement/estimation method.

RQ3. Are there any areas globally where $\Delta ET_{f\text{-}g}$ is positive?

H3: $\Delta ET_{f\text{-}g}$ is always negative at all locations on the globe.

I answer RQ1 and RQ2 by constructing a database of existing studies that measure or estimate ET rates of forests and grasslands using paired catchments, compare adjacent or proximal sites, or compute FGC with RS data or LSM. To answer RQ3, a global ET database (GETA2.0), will be used to determine if and where grasslands have higher ET than forests. Research began in June, 2015 and continued until March, 2016.

3.0 Methods

3.1 ΔET_{LCC} Database

3.1.1 Selection Criteria

The ΔET_{LCC} database was compiled with a goal of obtaining an exhaustive collection of data from existing global studies that compared forest and grassland ET and controlled for meteorological and landscape factors (Figure 3.1) (Appendix A2). Construction of ΔET_{LCC}, which contains 70 data points, follows the work of previously compiled syntheses by Hibbert (1967), Bosch and

Hewlitt (1982), Sahin & Hall (1996) and Brown et al. (2005), with the inclusion of EC, RS and LSM as methods of estimation/measurement. Forests in ΔET_{LCC} are defined as both natural forest cover (including evergreen broadleaf (EBF), deciduous broadleaf (DBF), evergreen needle leaf (ENF), deciduous needle leaf (DNF) and mixed forests (MXF), Amazon tropical (ATF) and "natural" forests (NF)) and tree plantations (TP). Grasslands (GRS) are defined as natural grasslands (GS), pasture (PA) and deforested lands (DF).

LCC analyses have typically employed the WB method with a PC experimental design (Bosch & Hewlitt, 1982, Brown et al., 2005, Dias et al., 2015). PC experiments have not been employed with EC, RS or LSM measurement methods, thus other experimental designs were included to accommodate these methods. Because EC, RS and LSM methods are used for a wide range of experimental designs, selection criteria were employed restrict studies to those controlling for climatic and environmental factors, as in PC experiments. Characteristics of ΔET_{LCC} and selection criteria used to assemble it are outlined in Table 3.1 and 3.2

Table 3.1. Selection Criteria for studies included in the ΔET_{LCC} database

Criteria Type	Selection Criteria
Climatic and environmental factors	Studies limited to paired catchments, adjacent or nearby* plots, and plot or catchment conversion via remotely sensed or land surface model
Temporal scale	Annual or multi-year averages of ET. Studies reporting in daily, monthly or seasonal ET were excluded.
Measurement units	Only studies that reported ET in a unit of measure (m, mm, inches) or a change in ET (in m, mm, inches) were included. Studies reporting change in % were excluded.
Treatment	Only studies that used catchments, plots or models where 100% of the area experienced treatment.
Land Cover Types	All forest types (including reforested species), grasslands, pasture. Irrigated crops were excluded.
Age of vegetation	All forest and grassland ages

*Nearby plots are defined as those located within a regional catchment that have been determined by the researcher to have similar enough characteristics to be controlled for climatic and environmental factors (Baldocchi & Ma, Dore et al, 2012)

Table 3.2. Summary of characteristics of the ΔET_{LCC} database

Characteristics of the ΔET_{LCC} Database		
	Total Data Points	70
Measurement / Estimation	Catchment Water Balance	37
Methods	Eddy Covariance	6
	Remote Sensing	6
	Land Surface Models	21
Forest Sub Species	Amazon Tropical Forest	18
	Hardwood Forest	4
	Deciduous Forest	4
	Evergreen Forest	4
	Tree Plantation	9
	Mixed Forest	18
	“Natural” Forest	8
	Other	5
Grassland Type	Natural Grassland	18
	Pasture	3
	Deforestation	38
	Not reported	11

Figure 3.1. Global distribution of studies in the ΔET_{LCC} database. Studies that did not report location are not represented.

3.1.2 Literature Search Methods

A number of interweb-based search methods were used to populate ΔET_{LCC}. Google and Google Scholar as well as the Dalhousie Libraries and the Web of Science search engines were explored using combinations of key terms and phrases summarized in Appendix 1. Cited references searches of papers and authors found from simple searches were explored through Web of Science. Requests for data or published papers were sent via email to researchers and managers of North American FLUXNET EC towers and experimental forests.

3.1.3 Analysis of ΔET_{LCC}

To answer RQ1, ET rates of 46 entries from ΔET_{LCC} were used to compare forest and grassland ET (Figure 4.1). 24 data points are not included in this analysis because they do not report forest and grassland ET rates. Because the forest and grassland ET data are not normally distributed, a Wilcoxon test was performed under the null hypothesis that forest ET > grassland ET.

To allow for a comparison of ΔET_{LCC} to Williams et al. (2012), 38 entries from ΔET_{LCC} are plotted in Budyko space (Figure 4.2). Because ΔET_{LCC} does not contain PET data, it was extracted from the WorldClim Global-PET dataset, a 30-second, temperature-based PET model (Trabucco et al., 2007). 32 data points are not included in this analysis because they did not report forest or grassland ET, P or latitude and longitude.

To answer RQ2, 58 data points from ΔET_{LCC} are plotted against P, with measurement and estimation methods symbolized by colour (Figure 4.4). 12 data points were left out of this analysis as they did not report P.

3.2 GETA2.0

3.2.1 GETA Database

The GETA database is a global dataset of annual actual ET comprised of 2363 points that represent 16 land cover types. Data have been collected from spatial scales ranging from small plots to large catchments using various measurement methods that include the WB, EC and energy balance (Ambrose & Sterling, 2014) (Appendix A3). For the purpose of this analysis, only natural forest (EBF, DBF, ENF, DNF, MXF) and GRS data have been used. Figure 3.2 shows a summary of this data. P and measurement type data are not complete in this dataset and thus will not be used. To obtain P values for the use in this analysis, values were extracted for each ET data point by geographic location (latitude, longitude) from the National Climate Centres` global P dataset, a LSM with a 6-hour time step and a spatial resolution of 1^{o} (Ngo-Duc et al., 2005).

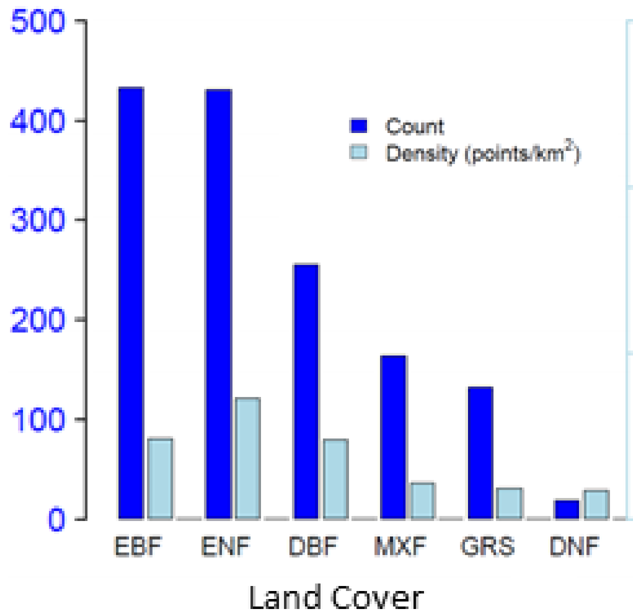

Figure 3.2. Summary of GETA2.0 data points by land cover. Adapted from (Ambrose & Sterling, 2014).

3.2.2 GETA 2.0 Forest and Grassland Raster Calculations

Ambrose & Sterling (2015) constructed global fields of ET from GETA 2.0 using a linear mixed effects model based on temperature, P and short-wave radiation as statistically-determined independent predictors. Global bands of ET were then extrapolated to produce 1-degree rasters for each LC type. LC rasters were masked to 5-minute cells in which each LC type appeared, based on global potential vegetation (Ramankutty & Foley, 1999) and anthropogenic vegetation (Sterling & Ducharne, 2008) producing a global annual actual ET projection (Ambrose & Sterling, 2015).

To answer RQ3, A simulation of forest to grassland conversion was performed using rasters of the 5 forest types (EBF, DBF, ENF, DNF, MXF), masked to the respective forests' natural LC range. The unmasked grassland raster was masked to a mosaic of all forests and a simple raster subtraction of the forest mosaic minus grassland was performed. To simulate grassland to forest conversion, each unmasked forest type was masked to the clipped grasslands raster. The grassland mask was then subtracted from each of the masked forest types, producing potential grassland to forest conversions for each forest type.

4.0 Results & Discussion

4.1 Forest and Grassland ET with Land Cover Change

Results indicate that in all studies in the ΔET_{LCC} database, forests had higher rates of ET, with a mean difference of 0.231 +/- 0.177 m/yr (Figure 4.1). Wilcoxon results give a P-value of 0.9996 at a 95% confidence interval, indicating that forest ET is greater than grassland ET. In the

Budyko plot (Figure 4.2), the evaporative indices of forests are greater than grasslands, though both forests and grasslands appear variable.

The result that forests have higher ET than grasslands agrees with the historical consensus on ET drivers with respect to land cover. Forests have higher leaf-area indices as well as deeper and more extensive root systems than grasses, allowing for higher interception of P, more uptake of infiltrated water and higher photosynthesis rates (Williams et al., 2012). Additionally, their canopy structure provides increased surface roughness, aiding in turbulent exchange from the well-coupled canopy to the overlying atmosphere and increasing the moisture gradient allowing for increased diffusive exchange of water vapour (Chapin et al., 2011). Numerous syntheses studies investigating impacts of land cover changes on ET rates support the result of forests having higher ET, including Hibbert (1967), Bosch & Hewlett (1982), Zhang et al. (2001) and Farley et al. (2005).

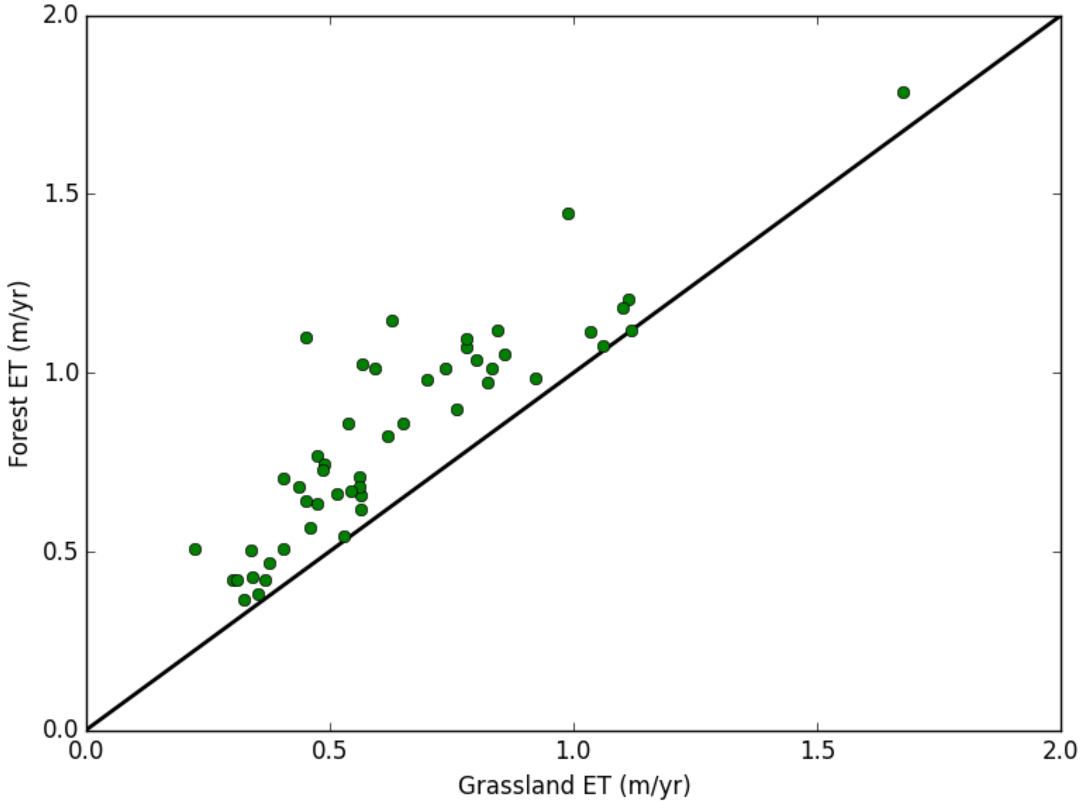

Figure 4.1. Forest ET vs. Grassland ET from the ΔET_{LCC} database

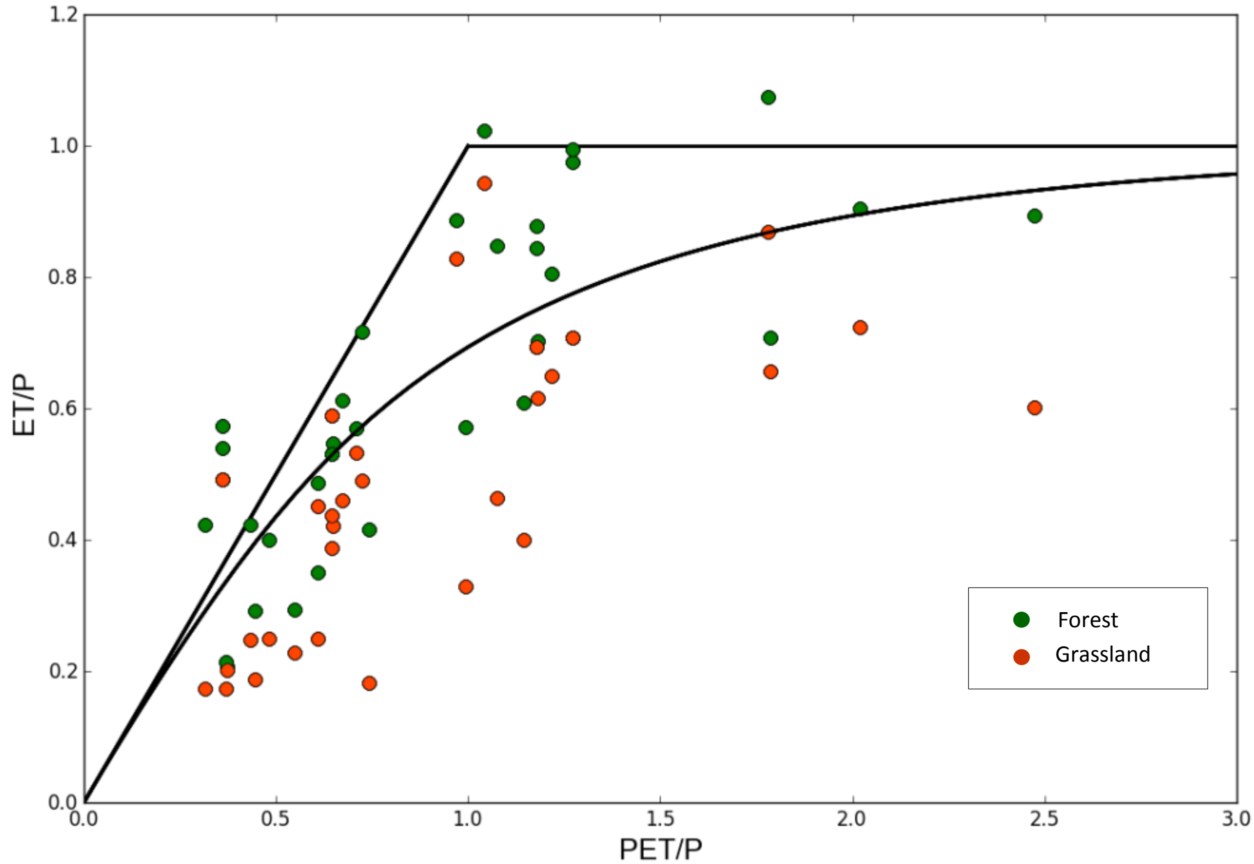

Figure 4.2. Budyko plot of forest and grassland entries from ΔET_{LCC}. Only 38 studies reported precipitation data and latitude/longitude used to obtain PET from Trabucco et al (2007).

The result of forest ET being greater than grassland is, however, in conflict with Williams et al. (2012). Williams' analysis used the Budyko framework to control for climatic variability between land cover types, allowing for a statistical comparison of ET using P and PET. Comparing in Budyko space, Williams et al. (2012) results do not agree with ΔET_{LCC}, which shows a large portion of grasslands plot below the curve and are in the energy limited region of Budyko space, while forests are closer to the curve as well as the energy and water limits. In Williams et al. (2012), the opposite seems to be true, with many forests below the curve and in the energy limited space, while grasslands plot the Budyko curve (Figure 4.3). It is important to note that, the PET values used in ΔET_{LCC} were the same for both forests and grasslands, where grasslands and forest would normally have different PET (Brauman et al., 2012; Wang & Dickson, 2012). In addition, PET data for ΔET_{LCC} are from the Global-PET dataset, a simplified, temperature-based model predicting PET (Trabucco et al., 2007). Thus, results from ΔET_{LCC} are of limited certainty. The following will discuss the limitations of Williams et al. (2012) regarding Budyko.

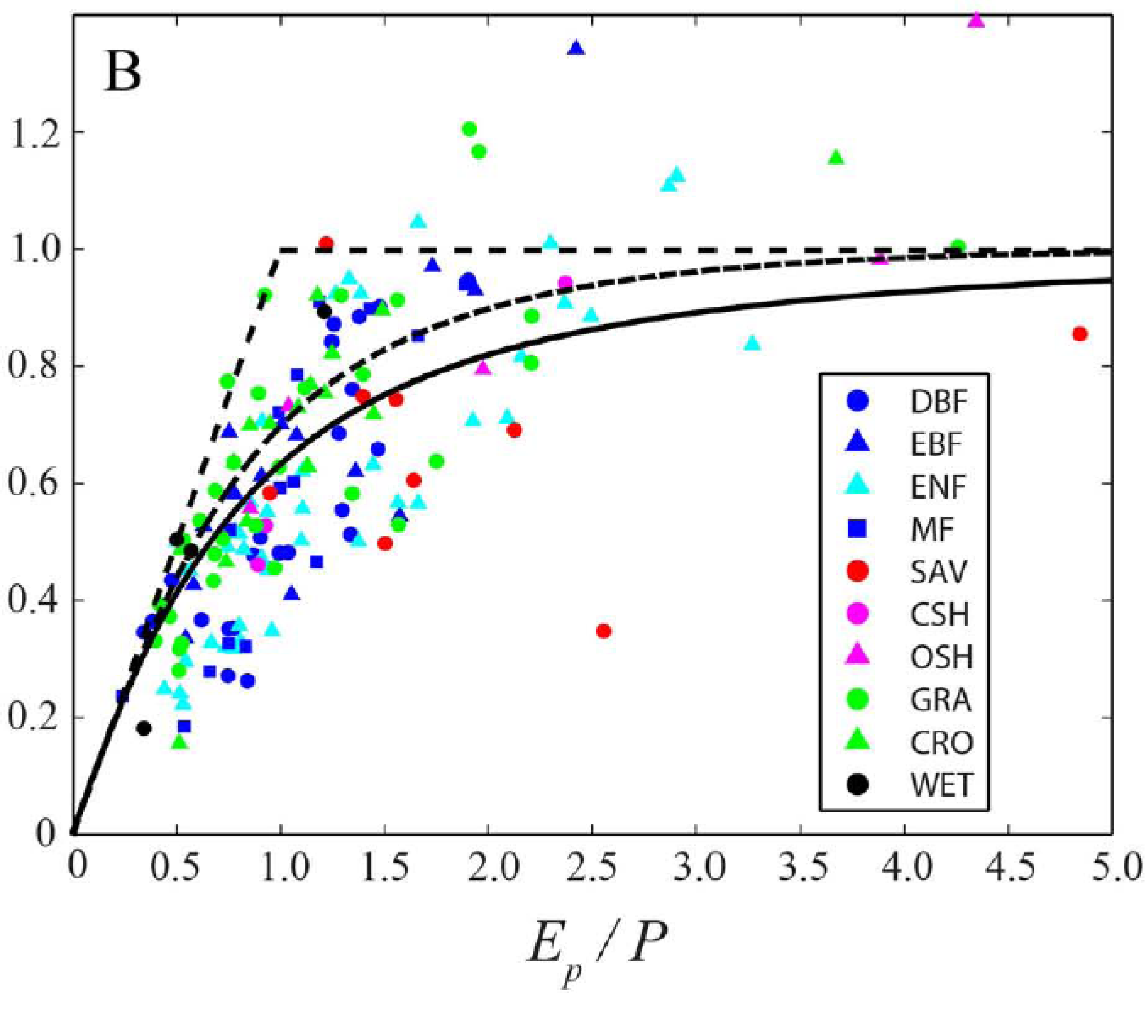

Figure 4.3 . Budyko plot from Williams et al. (2012)

The EC method and Budyko framework have limitations in measuring and comparing rates of ET, and results of Williams et al. (2012) appear to be in violation of these limitations. Budyko is employed with the assumption that the area of measurement is in a steady state, meaning that there are no changes to storage via soil moisture or snowpack, and phreatic uptake and run-on, or overland flow, are negligible (Williams et al., 2012). Donahue et al. (2007) notes that these assumptions and the Budyko framework are most reliable under longer temporal and larger spatial scales (>> 1 yr, > 1000 km^2) and short-term or small scale ($\leq$1-5 yrs, <1000 km^2) applications can be prone to variation in storage. This is because groundwater flow, soil moisture and run-on vary inter-annually over scales smaller than a medium catchment (1000-10000km^2) (Donahue et al., 2007). While forests are more capable of accessing deeper soil moisture, grasslands, especially in a scale smaller than a catchment, could be prone to changes in shallow soil moisture and run-on. As the EC measurements in Williams et al.(2012) are taken from small-scale measurement sites (inherent in EC) and at short temporal scales (median of 4 years of data), the results from this study contain some degree of uncertainty with respect to forest and grassland ET rates.

4.2 Bias in ET LCC Measurement and Estimation Methods

ΔET from is ΔET_{LCC} variable, ranging from 0.016 m/yr in lower P areas to 0.985 m/yr in higher P areas. Results indicate that the EC method produce the smallest differences between forest and grassland ET (ranging from 0.055 to 0.166 m/yr), with these observations occurring across the range of P (0.560 to 2.29 m/yr) (Figure 4.4). Conversely, studies using remotely sensed data were at the higher end of the ΔET values (ranging from 0.361 to 0.521 m/yr at P rates of 1.1 to 2.5 m/yr). Water balance and LSM studies show varied results, with water balance studies yielding a range of 0.016 to 0.457 m/yr across the range of P and LSM studies from 0.156 to 0.985 m/yr, all in the high range of P (2.01 – 2.94 m/yr). It is important to note that these results are not statistically significant due to a small sample size for EC and RS methods.

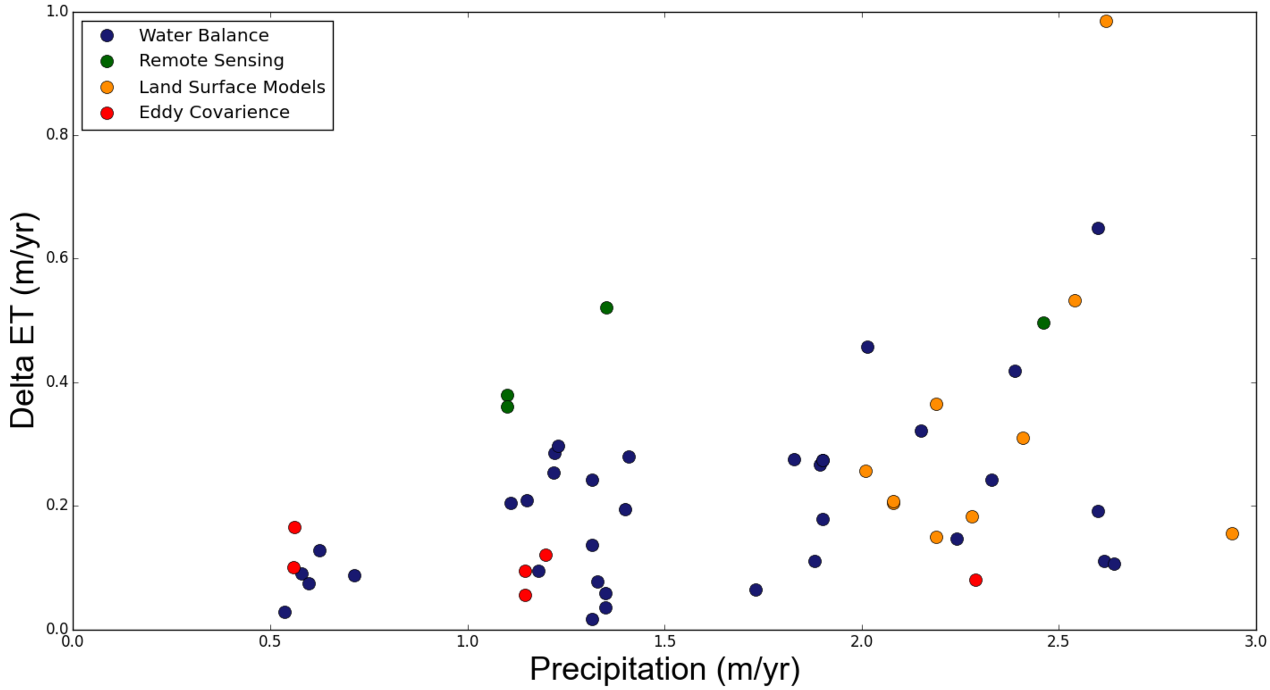

Figure 4.4. The difference between forest and grassland ET, computed as forest ET minus grassland ET, for 58 entries from ΔET_{LCC}.

While attempts to determine bias in ET measurement methods are of limited statistical significance, the results do have some support in the literature and thus may be of some value. Eddy covariance produced consistently lower ΔET values than WB, RS or LSM studies, displaying a smaller difference between forest and grassland ET. This could potentially be explained by EC bias caused by inaccurate measurement of weak turbulent fluxes and nocturnal ET (Wilson et al., 2002, Franssen et al., 2010, Novick et al., 2009). While it is not clear that energy balance bias of EC would disproportionately affect forest ET, it is clear that significant uncertainties exist in with the EC method and these need to be considered in any LCC investigation.

4.3 Areas where grassland ET is higher than Forest ET

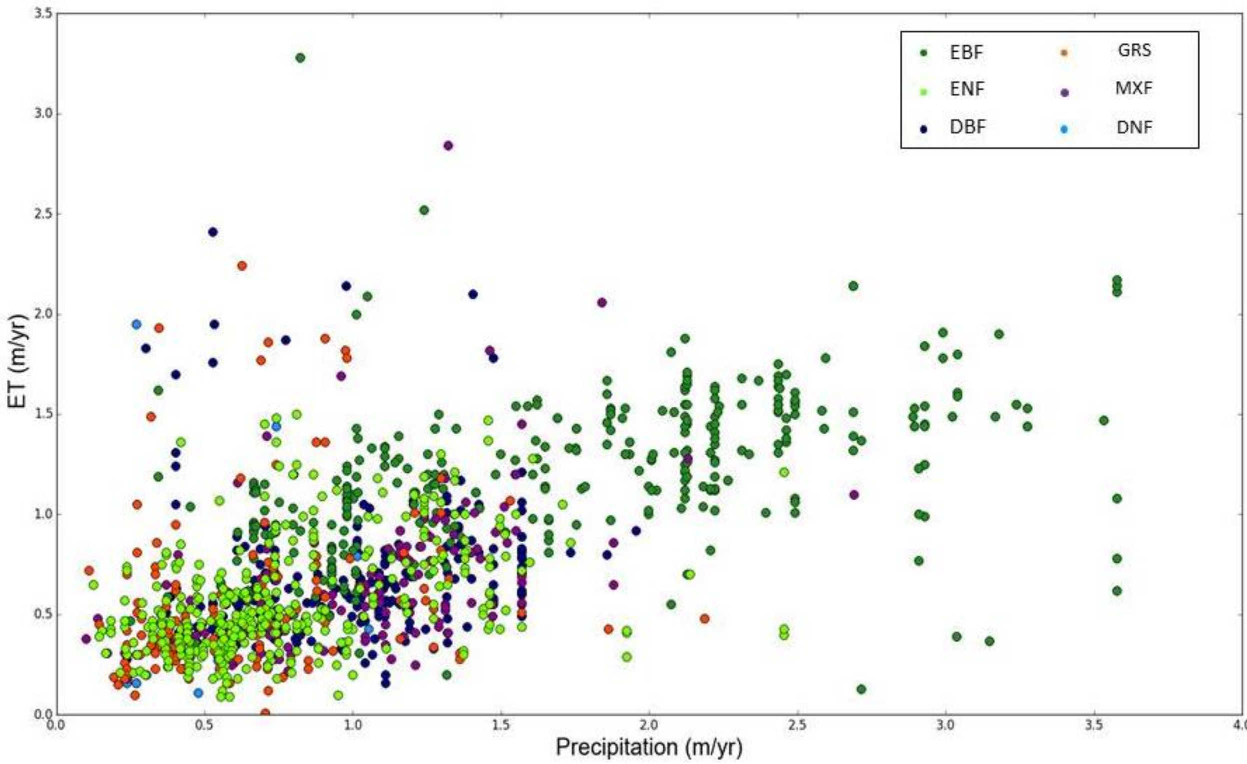

Figure 4.5. Forest and grassland ET and P from the GETA2.0 database. Forest species and grasslands are symbolized by colour.

Data of all land cover types shows significant scatter ET with only a weak relationship between ET and P (Figure 4.5). Grassland ET is represented in the higher ET range at P values below 1. To determine where these sites of high grassland ET are located, the GETA data points are plotted by latitude and longitude (Figure 4.6), where the 5 forest types and grasslands are symbolized and larger ET values represented by larger markers. Results from the forests to grasslands simulation (Figure 4.7a) shows that in general, forest ET is higher than grasslands, with a mean difference of 0.111 m/yr. Exceptions occur primarily in the northernmost regions and in localized areas at higher elevations of the Apls, Myanmar, Bangladesh and Alaska. Conversions of grasslands to forests (Figure 4.7b-f) show similar results with forest ET generally being greater the grassland and the mean difference of 0.142 m/yr.

Data and statistical models from GETA are in general agreement with the results from ΔET_{LCC}, but both disagree with the result from Brovkin et al. (2015). The HadGEM2 model, presented by Brovkin et al. (2015), is yet to be published and little information can be found regarding the prediction of increased ET with tropical deforestation (Pending response from Dr. Brovkin). Two other models were presented by Brovkin et al. (2015), EC-Earth and MPI-ESM, both showing a decrease in ET with the same tropical deforestation as HadGEM2, suggesting the HadGEM2 model may be uncertain. Further research is needed to determine whether the result from HadGEM2 is accurate.

Some exceptions where grassland ET is greater than forest appear in the simulated FGC and GFC (Figure 4.7) as well as in the lower P range of GETA2.0 data (Figure 4.5), and thus require further investigation. The most apparent exceptions in both FGC and GFC scenarios occur in the northernmost regions of Russia and Canada where significant areas appear to show grasslands have higher ET than forests. Inspection of the GETA database and ET modelling from Ambrose & Sterling (2014) indicates that these same regions are areas of greater uncertainty, especially with respect to grassland ET rates (Figure 4.8). Grassland predictors, as well as EBF, ENF and DBF, are underrepresented in the same areas that appear to have higher grassland ET (Figure 7), while DNF and MXF are better represented in these areas. Thus, significant extrapolation of modeled ET in these regions has created greater uncertainty, which may explain the contradiction of grassland ET.

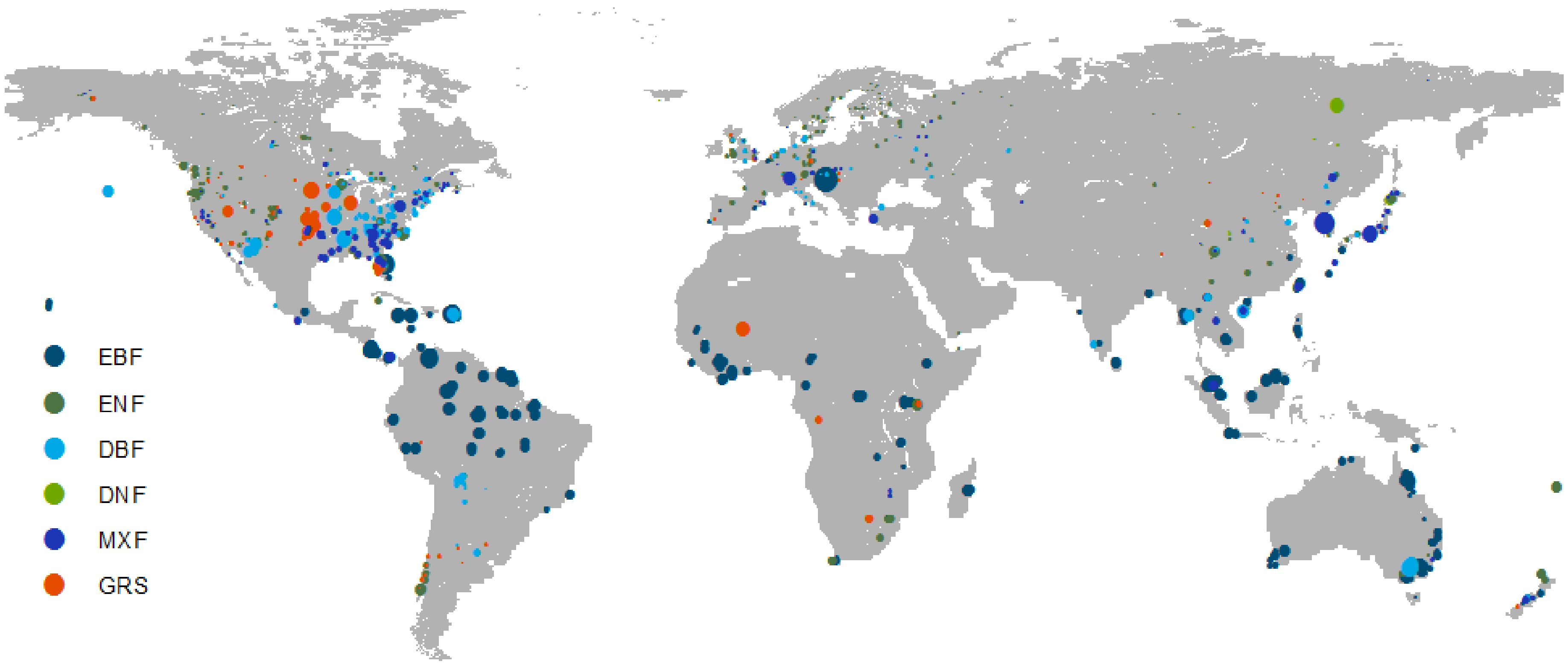

Figure 4.6. Map of GETA2.0 forest and grassland ET. Magnitude of ET is symbolized by marker size, with a larger marker representing higher ET.

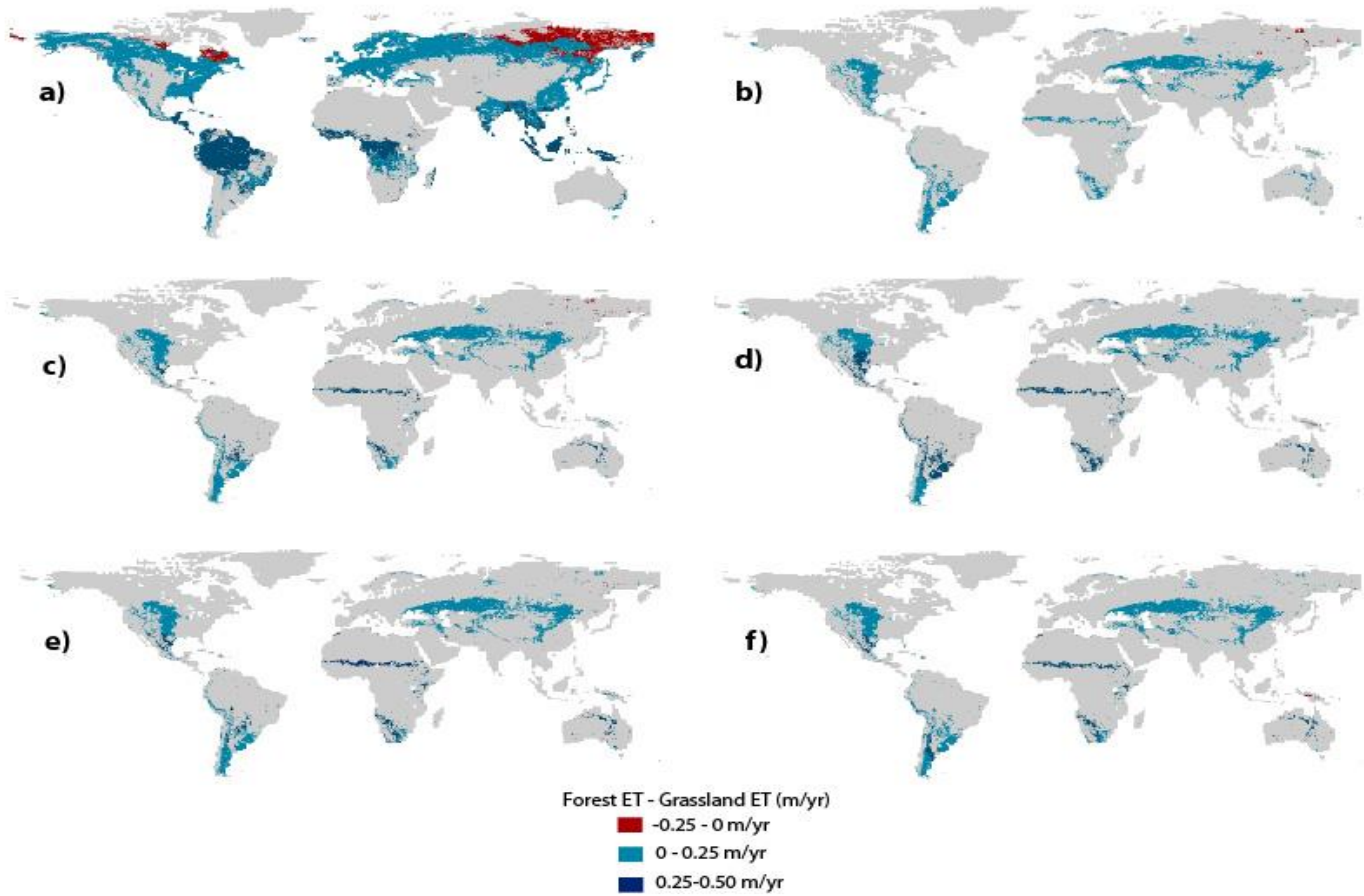

Figure 4.7. Forest to grassland (a) and grassland to forest (b-f) conversions modeled using ``Global Patterns of ET`` from Ambrose & Sterling (2014). a) all forests to grasslands, b) GRSs to MXF, c) GRS to ENF, d) GRS to EBF, e) GRS to DNF, f) GRS to DBF. Areas where grassland ET would be higher than forest are displayed in red, while higher forest ET is displayed in blue.

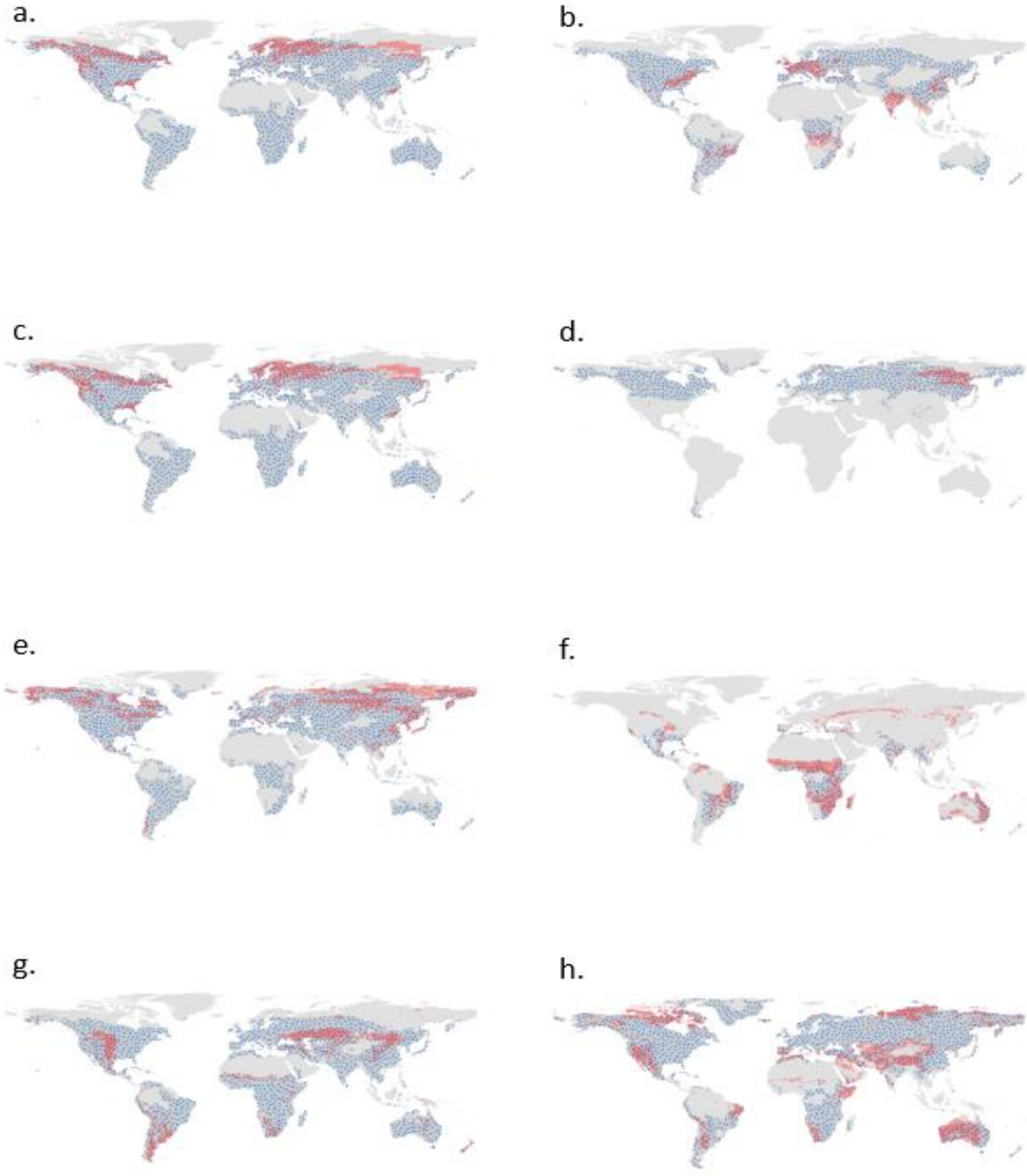

Figure 4.8. Areas where independent predictors (temperature, P, short wave radiation) (blue dots) intersect with LC types (red). a) ENF, b) DBF, c) ENF, d) DNF, e) MXF, f) SAV, g) GRS, h) SHR. Adapted from Ambrose & Sterling (2014).

Other noted exceptions in the Apls, Myanmar, Bangladesh and Alaska are not subjected to this same uncertainty and require additional investigation. Areas of higher grassland ET are all in mountainous regions where orography strongly affects weather patterns. Orographic enhancement of rainfall events including increased intensity, prolonged duration and higher overall totals, is common in these areas and is variable at smaller (<200 km) spatial scales on both seasonal and annual time scales (Anders et al., 2006, Pfister et al., 2005). In addition to spatial and temporal variability in P, topography causes spatial variability in incoming radiation and wind, main factors that drive ET (Liu et al., 2012). Thus, ET in these regions may be quite variable, and this uncertainty might help to explain the areas where grasslands appear to have higher ET than forests. There are, however, studies that support the result of higher grassland ET in mountainous regions. Research by Ataroff and Rada (2000) looked at the impacts of deforestation on hydrology in Andean cloud forests and found that the grasslands transpired a higher percent of P (66%) and had less runoff (2%) than forests. Additionally, Brauman et al. (2012) found that the PET for grasslands in higher than forests in an orography-influenced area of Hawaii.

High measurements of ET from GETA2.0 are located mainly in the central states of the US. Many of the high ET measurements come from areas that experience frequent severe thunderstorms, which may provide high P amounts that could lead to high ET. The appearance of these high ET measurements in the low P range may be a result of the NCC dataset from which P was obtained. Without further data including measured P and PET, discussion for this result is speculative and further work is required to determine if grasslands in these areas have higher ET than forests.

4.4 Limitations and Future Work

Results from both **ΔET_{LCC}** and GETA2.0 databases show that in general, when comparing rates of ET on a single plot or paired catchment, forests will have higher ET than grasslands. However, I am hesitant to claim the results are robust due to limitations of data used in both analyses. Many studies used to construct **ΔET_{LCC}** did not report data valuable to this analysis, such as forest and grassland ET values (reported ΔET), P, PET and location of study (latitude, longitude), while P and PET is also absent from many studies in GETA2.0. Additionally, spatial distribution of data in **ΔET_{LCC}** and GETA2.0 is uneven, with a higher concentration in mid-latitudes, and presents particular concern for the global F-G and G-F conversions which used extrapolated band of global ET (Ambrose & Sterling, 2014).

A more complete dataset for both the **ΔET_{LCC}** and GETA2.0 databases would allow for more robust analyses of LCC and more direct comparisons to the literature. For example, Budyko plots of **ΔET_{LCC}** and GETA2.0 (using site-specific P and PET) would allow for more direct comparisons to Williams et al. (2012). Because data from **ΔET_{LCC}** and GETA2.0 disagree with Williams et al. (2012), direct comparisons between the datasets would enable us to test if and how the results of Williams et al. (2012) were affected by violations in the assumptions of the Budyko framework.

A better representation of all measurement methods in **ΔET_{LCC}** database would provide a more substantial and statistically significant result, especially when looking for estimation and measurement bias. However, there appears to be a major gap in the literature regarding EC and RS measurements of forest to grassland LCC. The vast majority of EC studies do not compare forest and grassland ET in a before/after or paired plot scenario and instead compare ET with geographically dissimilar plots. RS studies tend to look at larger geographic areas with heterogeneous land cover and are thus not useful to study localized LCC.

Finally, improved spatial coverage of ground-based ET and meteorological measurements would improve the global state of knowledge and provide better tools for all other ET measurement and estimation methods (Miralles et al., 2011), including the global bands produced by GETA2.0. Combination methods (such as RS and LSMs) that use point-based observations to extrapolate and upscale ET and verify model outputs, appear to be the most promising in terms of improving our understanding of ET, at all scales (Miralles et al., 2011, Sato et al., 2015, Michel et al., 2016). A better understanding of the hydrologic cycle and its components at all scales is the key to improving our knowledge of how ET is affected by anthropogenic LCC.

5.0 Conclusions

The impacts of F-G LCC on ET rates were investigated in this study using two annual ET databases: 1. ΔET_{LCC}, a new database compiled for this study using published F-G and G-F experimental results and; 2. GETA2.0, a new dataset of global annual ET representing 16 land cover types. The conversion of forests to grasslands is a widespread anthropogenic LCC that can affect the local and regional hydrologic cycle and influence the water available for ecosystem and human consumption. Our understanding of how F-G LCC affects ET has become unclear due to recent publications by Williams et al. (2012) and Brovkin et al. (2015). This study sough to clarify the forest-grassland ET paradigm by answering:

Is ΔET always negative when natural forests are converted to grasslands?

Does $\Delta ET_{f\text{-}g}$ vary with ET measurement/estimation method?

Are there any areas globally where $\Delta ET_{f\text{-}g}$ is positive?

Through assembly and analysis of the ΔET_{LCC} database, I determined that in a F-G or G-F scenario, ΔET is always negative. This ΔET result agrees with the historical consensus in the literature but opposes recent findings from Williams et al. (2012) and Brovkin et al. (2015). An attempt to determine if $\Delta ET_{f\text{-}g}$ varies with ET measurement/estimation methods found that RS produced the largest ΔET, WB and EC had varying results and the EC method produces the smallest ΔET, though these results were not statistically significant due to a lack of data points. Finally, I used Global bands of ET from the GETA2.0 database to establish if there are any areas globally where $\Delta ET_{f\text{-}g}$ are positive. Results from GETA2.0 showed that generally, forest ET is higher than grassland, and while some exceptions were found, these exceptions are located in areas of high model uncertainty and thus are uncertain themselves.

Both ΔET_{LCC} and GETA2.0 datasets are missing key data, including P and PET, which would provide an opportunity for a more robust analysis of ET data. Additionally, a better representation of ET estimation and measurement methods in ΔET_{LCC} in the literature would allow for a more substantial result when looking for bias in these methods. Perhaps the most significant result in this study is the inability to collect this important data, which itself reflects the state of the research and uncertainty regarding the impacts of LCC on ET. It is clear that more ET data needs to be collected around the globe, and research and measurement methods need to be better integrated, in order to produce more reliable ET models for LCC and the hydrologic cycle on all scales.

6.0 References

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Appendix

A1.

Key Search terms and phrases used to populate the ΔET_{LCC} Database		
Evapotranspiration	Land Cover Change	Eddy Covariance
Change in Water Yield	Deforestation	Remote Sensing
Energy Balance	Afforestation	Water Balance
Latent Heat	Forest	Global Circulation Model
	Grasslands	Pasture

A2. ΔET_{LCC} Database

ID	Land Cover Change (forest-grassland)	Authors	Year	Journal	Forest ET (m/yr)	Grassland ET (m/yr)	ΔET (m/yr)	Method	Precip. (m/yr)
1	ATF-DF	Lean & Rowntree, 1997	0	Journal of Climate			0.296	ABRACOS	
2	ATF-DF	Hahman & Dickinson, 1995	1985	Journal of Climate	0.972	0.823	0.149	CCM	2.19
3	ATF-DF	McGuiffe et al, 1995	0	Global and Planetary Change			0.231	CCM	
4	HWF - GS	Stoy, 2006	2001-2004	Glocal Change Bioogy	0.658	0.563	0.095	Eddy Covariance	1.145
5	PP - GS	Stoy, 2006	2001-2004	Glocal Change Bioogy	0.618	0.563	0.055	Eddy Covariance	1.145
6	NHF-GS	Wolf et al, 2011	2008	Ecosystems	1.114	1.034	0.08	Eddy covariance	2.289
7	OSAV-GS	Baldocchi & Ma, 2013	2004-2010	International Meteorological Instituie in Stockholm	0.503	0.338	0.1656	Eddy Covarience	0.562
8	DBF-GS (BUR)	Dore et al, 2012	2006-2010	Glocal Change Bioogy	0.506	0.405	0.101	Eddy Covarience	0.5597
9	ENF-DF	Paul-Limoges et al, 2015	1999-2007	Agricultural and Forest Meterology	0.42	0.2997	0.1203	Eddy Covarience	1.198
10	ATF-DF	Zeng et al., 1996		American Meteorological Society			0.73	ENSO	
11	ATF-DF	Dickinson, Henderson-Sellers, 1988		Q.J.R. Meterol. Soc.			0.1825	GCM	2.28
12	ATF-DF	Dickinson & Kennedy, 1992		Geophysical Research Letters			0.256	GCM	2.01
13	ATF-DF	Lean, Warrilow, 1989		Letters to Nature			0.31	GCM	2.41
14	ATF-DF	Lean, 1993		Quarterly Journal of the Royal Meteorological Society			0.204	GCM	2.08
15	ATF-DF	Sud et al., 1990		Agricultural and Forest Meteorology			0.438	GCM	
16	ATF-DF	Sud et al., 1996b		American Meteorological Society			0.365	GCM	2.19
17	ATF-DF	Polcher & Laval, 1994b		Journal of Hydrology			0.985	GCM	2.62
18	ATF-DF	Polcher & Laval, 1994b		Journal of Hydrology			0.532	GCM	2.54
19	ATF-DF	Mylne & Rowntree, 1991		Climatic Change			0.176	GCM	n/r
20	ATF-DF	Pitman et al, 1993		International Journal of Climatology			0.207	GCM	2.08
21	ATF-DF	Pitman et al, 1993		International Journal of Climatology			0.156	GCM	2.94
23	TDF-GS	Twine, 2004	1958-1995	Journal of Hydrometerology			0.158	IBIS Land Surface Model (Integrated	N/R

								biosphere Simulator)	
24	NF-GS	Nosetto et al, 2011	2000-2001	Agriculture, Ecosystems and Environment	1.073	0.78	0.379	LANDSAT & HYDRUS (W.B)	1.1
25	TP-GS	Nosetto et al, 2011	2000-2001	Agriculture, Ecosystems and Environment	1.094	0.78	0.361	LANDSAT & HYDRUS (W.B)	1.1
26	ETP - GS	Nosetto,2005	2003	Global Change Biology	1.148	0.627	0.521	LANDSAT / energy balance (net radiation)	1.352
27	ATF-DF	Nobre et al, 1991		Journal of Climate			0.496	NMC Global Spectral Model	2.46
30	DF - GS	Dunn & Mckay, 1995	1985-1989	Journal of Hydrology	0.633	0.475	0.158	SHETRAN Model (GCM)	0.6-1.5
31	EF - GS	Dunn & Mckay, 1995	1985-1989	Journal of Hydrology	0.766	0.475	0.291	SHETRAN Model	0.6-1.5
33	ENF-WGS	Mao, 2009	1975-1995	Journal of Hydrology	0.709	0.561	0.148	VIC Model	0.808
34	DBF-WGS	Mao, 2009	1975-1995	Journal of Hydrology	0.682	0.561	0.121	VIC Model	0.808
35	NF-GS	Yang et al, 2014	2009	Journal of Arid Land	0.365	0.324	0.041	VIC Model (water and energy balance)	0.451
38	EUP - PA	Adelana, 2015	2011-2012 avg	Hydrological Processes	0.671	0.543	0.128	Water Balance	0.624
39	TP-GS	Marc & Robinson, 2007	1972-1982	Hydrology & Earth System Science	0.643	0.451	0.192	Water Balance	2.6
42	NF-DF	Hibbert, A.R. (1969)	1940	Water Resources Research	1.12	0.844	0.276	Water Balance	1.829
43	NF-DF	Hibbert, A.R. (1969)	1941	Water Resources Research	1.037	0.8	0.267	Water Balance	1.895
44	MF-DF	Hibbert, A.R. (1969)	1919	Water Resources Research	0.38	0.352	0.028	Water Balance	0.536
45	MF-DF	Hibbert, A.R. (1969)	1948	Water Resources Research	0.541	0.53	0.11	Water Balance	2.616
46	MF-DF	Hibbert, A.R. (1969)	1956	Water Resources Research	1.446	0.989	0.457	Water Balance	2.014
47	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1947-1948	Journal of Hydrology	0.566	0.46	0.106	Water balance	2.641
48	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1962-1965	Journal of Hydrology	1.012	0.594	0.418	Water balance	2.388
49	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1974	Journal of Hydrology	0.86	0.538	0.322	Water balance	2.15
50	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1975	Journal of Hydrology	0.68	0.438	0.242	Water balance	2.33
51	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1940	Journal of Hydrology	1.011	0.737	0.274	Water balance	1.9
52	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1963	Journal of Hydrology	1.011	0.833	0.178	Water balance	1.9
53	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1963	Journal of Hydrology	0.661	0.514	0.147	Water balance	2.24
54	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1941	Journal of Hydrology	1.12	1.119	0.274	Water balance	1.9

55	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1956-1957	Journal of Hydrology	0.986	0.922	0.064	Water balance	1.73
56	MF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1940	Journal of Hydrology	1.207	1.113	0.094	Water balance	1.18
58	MF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1963-1964	Journal of Hydrology			0.035	Water balance	1.35
59	MF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1963-1964	Journal of Hydrology			0.059	Water balance	1.35
60	PF-Df	Bosch, J.M & Hewlett, J.D. (1982)	1970	Journal of Hydrology	1.18	1.102	0.078	Water balance	1.33
61	HWF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1965	Journal of Hydrology	0.509	0.223	0.286	Water balance	1.22
62	HWF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1974-1975	Journal of Hydrology	0.743	0.489	0.254	Water balance	1.219
63		Bosch, J.M & Hewlett, J.D. (1982)	1971	Journal of Hydrology	0.703	0.406	0.297	Water balance	1.23
64	JUPY-DF	Bosch, J.M & Hewlett, J.D. (1982)	1963	Journal of Hydrology			0	Water balance	0.457
65		Bosch, J.M & Hewlett, J.D. (1982)		Journal of Hydrology	1.1	0.45	0.65	Water balance	2.6
66	NF-DF	Bosch, J.M & Hewlett, J.D. (1982)		Journal of Hydrology	0.86	0.651	0.209	Water balance	1.15
67		Bosch, J.M & Hewlett, J.D. (1982)		Journal of Hydrology	0.823	0.618	0.205	Water balance	1.11
68	MF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1970	Journal of Hydrology	0.467	0.376	0.091	Water balance	0.579
69	MF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1970	Journal of Hydrology	0.42	0.368	0.074	Water balance	0.597
70	MF-DF	Bosch, J.M & Hewlett, J.D. (1982)	1970	Journal of Hydrology	0.422	0.31	0.112	Water balance	n/r
72	ATF-GS	Dias et al (2015)	2007-2010	Journal of Hydrology	1.025	0.567	0.458	INLAND Model (GCM)	1.301
73	Afforest	Sahin & Hall (1996)	1962	Journal of Hydrology	0.98	0.7	0.28	Water Balance	1.41
74	NF-DF	Sahin & Hall (1996)	1982	Journal of Hydrology	1.786	1.676	0.11	Water Balance	1.88
75	NF-GS	Sahin & Hall (1996)	1964	Journal of Hydrology	1.052	0.857	0.195	Water Balance	1.4
76		Andreassian (2004)		Journal of Hydrology	0.429	0.341	0.088	Water Balance	0.712
77		Andreassian (2004)		Journal of Hydrology	0.727	0.485	0.242	Water Balance	1.317
78		Andreassian (2004)		Journal of Hydrology	1.076	1.06	0.016	Water Balance	1.317
79		Andreassian (2004)		Journal of Hydrology	0.896	0.76	0.136	Water Balance	1.317

A3. The GETA2.0 Database can be requested at http://www.sterlinglab.ca/