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2 **Evapotranspiration is resilient in the face of land cover and climate change in a**

3 **humid temperate catchment**

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23

24 **Abstract**

25 In temperate humid catchments, evapotranspiration returns more than half of the annual

26 precipitation to the atmosphere, thereby determining the balance available to recharge

27 groundwaters and support stream flow and lake levels. Changes in evapotranspiration

28 rates and therefore catchment hydrology could be driven by changes in land use or

29 climate. Here we examine the catchment water balance over the past 50 y for a catchment

30 in southwest Michigan covered by cropland, grassland, forest, and wetlands. Over the

31 study period about 27% of the catchment has been abandoned from row-crop agriculture

32 to perennial vegetation and about 20% of the catchment has reverted to deciduous forest,

33 and the climate has warmed by 1.14°C. Despite these changes in land use, precipitation

34 and stream discharge, and by inference catchment-scale evapotranspiration, have been

35 stable over the study period. The remarkably stable rates of evapotranspirative water loss

36 from the catchment across a period of significant land cover change suggest that rainfed

37 annual crops and perennial vegetation do not differ greatly in evapotranspiration rates,

38 and this is supported by measurements of evapotranspiration from various vegetation

39 types based on soil water monitoring in the same catchment. Compensating changes in

40 the other meteorological drivers of evaporative water demand besides air temperature—

41 wind speed, atmospheric humidity, and net radiation—are also possible, but cannot be

42 evaluated due to insufficient local data across the 50-y period. Regardless of the

43 explanation, this study shows that the water balance of this landscape has been resilient in

44 the face of both land cover and climate change over the past 50 y.

45 **Keywords:** evapotranspiration, evaporation, crops, forest, crops, land use, climate

46 change

47   **1. Introduction**

48   In temperate humid catchments, evapotranspiration (ET) returns more than half of

49   the annual precipitation to the atmosphere (Hanson, 1991; Williams *et al.,* 2012; Zhang *et*

50   *al.,* 2016), mainly during the growing season by plant transpiration. The balance between

51   precipitation and ET recharges groundwaters and supports stream flow and lake levels.

52   Paired catchment studies often have shown that changes in the nature of the vegetation

53   cover, especially deforestation or afforestation, alter ecosystem ET rates and thereby

54   change stream flows (Bosch and Hewlett, 1982; Hornbeck *et al.,* 1993; Zhang *et al.,*

55   2001; Price, 2011; Brown *et al.,* 2005 and 2013). However, these studies are often

56   conducted in small experimental catchments and generally compare stream water yields

57   between two kinds of perennial vegetation (woody and herbaceous).

58   There have been fewer catchment-scale comparisons of water yield from annual

59   vegetation such as maize (*Zea mays*, known as corn in the U.S.) and soybean (*Glycine*

60   *max*) vs. perennial vegetation such as forest or grasslands (Price, 2011), yet land cover

61   change from perennial vegetation to cropland and vice versa has occurred throughout the

62   world as a result of agricultural expansion and contraction. In eastern North America, the

63   original forests and grasslands were largely converted to agricultural lands by European

64   settlers, but since the mid 1900s a substantial fraction of the converted land has reverted

65   back to successional fields and forests as the more marginal agricultural lands were

66   abandoned due to low profitability, poor suitability to mechanized cultivation, and

67   concerns about soil erosion and degradation (Houghton and Hackler 2000; Ramankutty *et*

68   *al.,* 2010).

69   Land cover in agricultural regions is expected to continue to change in the future.

70   As grain crops have become more profitable over the past decade due to global demand

71   for food and US policies that support ethanol production from maize, more land in

72   grasslands (including CRP land) is being converted to grow maize and soybean (Lark *et*

73   *al.,* 2015). Meanwhile, successional ecosystems are becoming mature forests in many

74   locations (Pugh, 2015). Climate change and invasive plant species will increasingly drive

75   changes in the nature and phenology of vegetation communities (Simberloff, 2000;

76   Parmesan and Hanley 2015). Further changes to the nature of vegetation in agricultural

77   landscapes may occur if cellulosic biofuel crops are increasingly grown in the future

78   (Gelfand *et al.,* 2013).

79   Recently we reported ET measurements in candidate cellulosic cropping systems

80   at a location in southwest Michigan, USA using two distinct approaches: 1) by

81   monitoring soil water content with time domain reflectometry in annual crops (maize) as

82   well as perennial grasslands and hybrid poplar stands (Hamilton *et al.,* 2015); and 2) by

83   monitoring energy and water vapor fluxes using eddy covariance in maize, switchgrass,

84   and prairie at a nearby site (Abraha *et al.,* 2015). Results suggest strikingly similar

85   growing-season ET among these diverse plant systems, raising the question of whether

86   land cover changes would significantly affect ET in the Midwest U.S., as suggested in

87   some modeling studies (e.g., Le *et al.,* 2011; VanLoocke *et al.,* 2012; Zhuang *et al.,*

88   2013).

89   The objective of this study is to examine trends in ET over 50 y in a particularly

90   well-characterized, temperate humid catchment that has experienced significant land

91   cover change, but without the complications of urbanization, dams, and stormwater

92   management changes that are typical of larger catchments. We infer ET from the balance

93   between precipitation and discharge, and the results are compared with our independent

94   measurements of ET made on annual and perennial vegetation in the same catchment.

95

96   **2. Methods**

97   *2.1 Study site*

98   Augusta Creek is a 3rd-order stream in southwest Michigan (Kalamazoo and Barry

99   counties) that drains a predominantly rural landscape (95 km^2) composed of a mosaic of

100   forest, fallow fields, annual crops, wetlands, lakes, light residential development, and golf

101   courses (Figure 1). There are no impervious surfaces or storm drainage systems that drain

102   into the stream above the discharge measurement point, and urban land use covers just

103   2.4% of the catchment (land cover proportions over the 50-y period are presented later).

104   The stream is groundwater-fed, gaining water along most of its length. Its tributaries

105   emanate from wetlands or small lakes, and prairie fen wetlands line much of the stream

106   channels.

107   The stream runs through deep glacial deposits that lie well above the bedrock. The

108   most common soils in upland areas are well-drained Typic Hapludalfs developed on

109   postglacial terrain (Thoen, 1990), and there is little to no overland flow from upland areas

110   to the stream due to the high permeability of these coarse-textured soils (Rheaume,

111   1990). Irrigation of crops was rare in the area until very recently; some expansion has

112   taken place since 2005, supplied by groundwater wells.

113   Augusta Creek is in the vicinity of the W.K. Kellogg Biological Station (KBS),

114   where we conduct agricultural experiments under the aegis of the Great Lakes Bioenergy

115   Research Center (GLBRC) and KBS Long Term Ecological Research site

116   (www.lter.kbs.msu.edu; 42.3956° N, 85.3749° W and 288 m asl). Mean annual air

117   temperature is 10.1 °C and annual precipitation is 1005 mm, 511 mm of which falls as

118   rain during the May-Sep growing season (1981–2010) (NCDC 2013). In this region ET is

119   normally water–limited during the warmer part of the year (i.e., during at least part of the

120   growing season), and energy–limited during the cooler months (McVicar *et al.*, 2012a).

121

122   *2.2 Land cover changes*

123   Land cover for 1960 was estimated from georectified and mosaicked aerial photographs

124   in a geographic information system (ArcGIS). The catchment boundaries above the

125   discharge measurement point (US Geological Survey; Hydrologic Unit Codes

126   04050003040060 plus 04050003040070) and wetlands and lakes (National Wetlands

127   Inventory: http://www.fws.gov/wetlands/) were overlain on the aerial photo mosaic and

128   land cover was examined in the upland portions of the catchment. Based on the National

129   Wetlands Inventory, wetlands and lakes contiguous with the stream system amount to

130   15.9 km^2, or 16.6 % of the catchment above the discharge measurement point. Isolated

131   wetlands and small lakes also occur throughout the upland catchment, covering 5.2% of

132   its area. Wetland areas were assumed to be constant over the study period; there has been

133   no wetland drainage or creation in the catchment since 1960, and within the area mapped,

134   wetland boundaries generally include intermittently wet soils with high water tables as

135   well as areas with surface water.

136   Land cover for 2014 was estimated from the Cropland Data Layer

137   (http://nassgeodata.gmu.edu/CropScape/). For this purpose, we combined all field crops

138   (primarily maize, soybean and small grains) into the annual crop category, and all forests

139   (deciduous and coniferous) into the forest category. Conifers are not native to the upland

140   landscape here, but have been planted throughout the catchment; their total area as of

141   2014 amounts to ~3% of the total forest area and 1% of the upland catchment. The

142   grassland and pasture category includes hay as well as fallow fields (no native grassland

143   remains). The width of rural roads was exaggerated 3–5 fold in the Cropland Data Layer,

144   presumably due to automated classification of mixed pixels, so vegetated edges of

145   roadways were manually reclassified as grasslands. Land cover for an intermediate date

146   (1978), based on aerial photo interpretation, was available from the Michigan Resource

147   Inventory System (MIRIS) (http://www.ciesin.org/IC/mdnr/mrip.html); this data set was

148   comparable for forest but combines annual crops with some kinds of pasture, and was

149   therefore not compared for those categories.

150

151   *2.3 Discharge and climate records*

152   The US Geological Survey has monitored the discharge of Augusta Creek below the

153   lowermost tributary inflow since 1964 (station 04105700). The long-term mean discharge

154   at this point, which drains 95.3 km^2, is 1.28 m^3 s^{-1}. Daily discharge measurements for

155   October 1964 through September 2014 were partitioned into baseflow and stormflow

156   using the Web-based Hydrograph Analysis Tool (WHAT) described by Lim *et al.*,

157   (2005). Mean annual baseflow and stormflow discharges were calculated on a standard

158   U.S. water-year basis beginning on 1 October of each year, representing the transition

159   between warm and cool seasons, and water years are labeled by the starting year (i.e.,

160   water year 1964 is 1 October 1964–30 September 1965).

7

161   Climate data were drawn from several sources and compiled on a water-year

162   basis. Precipitation observations are from at least three stations (except 1992 which has

163   two) distributed across the catchment from north to south (Figure 1). Air temperature,

164   saturated vapor pressure, and drought index data were obtained from the Midwest

165   Regional Climate Center (http://mrcc.isws.illinois.edu/).

166

167   *2.4 Estimation of evapotranspiration from water balances*

168   Evapotranspiration has often been estimated from catchment water balances (e.g., Zhang

169   *et al.,* 2016). For Augusta Creek, the water balance for the upland portion of the

170   catchment was determined as the difference between annual totals of precipitation falling

171   on the uplands (i.e., the catchment excluding wetlands and lakes contiguous with the

172   stream channels) and the annual stream baseflow discharge. Isolated lakes and wetlands

173   were included in the upland catchment area. The difference between precipitation inputs

174   on the uplands and stream baseflow outputs is therefore considered to represent the ET of

175   the upland catchment.

176   This approach to ET estimation assumes that stormflow represents direct capture

177   of precipitation from the wetlands and lakes contiguous with the stream system, whereas

178   baseflow represents infiltration and percolation of precipitation falling on the upland

179   catchment. The validity of this assumption is supported by the water balance calculations

180   (see Results below) as well as the high permeability of the soils in the uplands (Rheaume,

181   1990). Other assumptions that are reasonable in this case include no inter-basin transfers

182   of water, which is true in this catchment, and no significant trend in water storage in the

183   aquifer or surface water bodies over the study period. Although there are no continuous

184   water table measurements spanning this study period, water levels of local lakes that are

185   connected to the groundwater have shown no unidirectional trend since the late 1960s

186   (see Figure S1 for an example of water level data for a lake in the Augusta Creek

187   catchment). Additional evidence for no interannual trend in groundwater levels is

188   provided by a compilation of static water level measurements that are made when

189   residential water supply wells are constructed, which shows no trend over the study

190   period (Figure S2).

191

192   *2.5 Evapotranspiration estimation from soil water content measurements*

193   Since 2009, soil water profiles throughout the root zone and below were monitored

194   hourly using permanently installed, horizontally inserted time domain reflectometry

195   (TDR) probes at depths of 20, 35, 50, 65, 90 and 125 cm as well as a vertically inserted

196   probe at 0–10 cm depth. Our methods for estimating ET from soil water profiles are

197   described by Hamilton *et al.* (2015), who presented data on six biofuel cropping systems

198   harvested each fall. The TDR measurements provide an estimate of ET when daily

199   drawdowns in soil water can be measured and the soil water content is below its drained

200   upper limit, which is typical of most of the growing season. The sum of the daily

201   drawdowns in soil water content over the entire profile (0-150 cm) across the growing

202   season provides an estimate of ET; on days when new infiltration of rain water prevented

203   a measurable soil water drawdown, we estimated ET using a crop growth model (Basso

204   and Ritchie, 2012).

205   Here we present the mean ET rates for three of those systems that resemble

206   vegetation found on the broader landscape: 1) continuous no-till maize; 2) a restored

207   native prairie planted with 18 species of forbs and grasses; and 3) a hybrid poplar

208   plantation (*Populus nigra* × *P. maximowiczii 'NM6'*). In addition, we present comparable

209   water use measurements for three other systems in the same vicinity: 1) a fallow field

210   abandoned from row-crop agriculture in 2008 and harvested each fall; 2) a mature

211   deciduous forest (>50 y old) dominated by sugar maple (*Acer saccharum*), red oak

212   (*Quercus rubra*) and hickory (*Carya* spp.) trees; and 3) an early successional forest (ca.

213   25 years old) dominated by shrubs including autumn olive (*Elaeagnus umbellata*) and

214   honeysuckle (*Lonicera* sp.*) as well as a few medium-sized sugar maple and black cherry

215   (*Prunus serotina*) trees.

216

217   **3. Results**

218   *3.1 Land use and climate changes*

219   Maize has been the dominant agricultural crop over the 50-y study period with the

220   balance of harvested crops shifting increasingly to soybean since the 1970s, as in the

221   greater Midwest US region (Gage *et al.,* 2015). Data on Kalamazoo County from the

222   annual Census of Agriculture (U.S. Department of Agriculture:

223   http://www.agcensus.usda.gov/) indicate that in 1964 maize accounted for 69% of

224   harvested cropland, soybean for 5.7%, and the balance was mostly oats with some barley

225   and wheat. By 1987 maize was 58% and soybean 28% of harvested cropland, and by

226   2007 these two crops accounted for 64% and 32% of the harvested cropland.

227   Land cover in the upland catchment changed significantly between 1960 and 2014

228   (Figure 2). The proportion of the upland catchment in annual crops decreased from 57 to

229   30%, while forest increased from 15 to 35%. The proportion of grassland remained

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230   similar, although only 20% of the 1960 upland grassland was still grassland in 2014;

231   most of the 1960 grassland became forest (43%) or cropland (22%), while some newly

232   abandoned cropland became grassland. The 1978 MIRIS land cover data (not shown; see

233   Methods) indicate that 94% of the forest present in 2014 existed by 1978, so most

234   reforestation began between 1960–78. Urban and residential development represents a

235   small fraction of the catchment (<2.4%), not including golf courses created during the

236   study period that covered 4.5% of the upland catchment by 2014 (the golf courses

237   occasionally irrigate during dry summers but are not significant water users at the

238   catchment scale). Similar changes in land cover occurred in adjacent catchments.

239   Annual precipitation for the Augusta Creek catchment over the 50 y averaged 948

240   ± 118 mm y^{-1} with no linear temporal trend (p = 0.93) (Figure 3a). No linear trend exists

241   in mean annual values for either the Palmer Drought Severity Index or the Palmer

242   Hydrological Drought Index (p = 0.34 and 0.67, respectively; Figure S3).

243   One or more of the four meteorological variables that control atmospheric

244   evaporative demand—wind speed, atmospheric humidity, net radiation, and air

245   temperature—could have changed over the 50 y, as global- and continental-scale analyses

246   have indicated significant changes in these variables in recent decades (Wild, 2009;

247   Willett *et al.,* 2008; McVicar *et al.,* 2012b). The effects of changes in these variables on

248   atmospheric evaporative demand could be to enhance or counteract each other, and the

249   resultant effect on ET is particularly important where evaporation is limited by energy

250   rather than water (e.g., decreasing wind speeds tend to counteract the effect of increasing

251   temperatures: McVicar *et al.,* 2012a, b). The region has experienced a 1.14°C increase in

252   mean annual air temperature (50-y mean = 8.95°C) which in turn equates to a 0.90

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253   millibar (mb) increase in saturated vapor pressure (50-y mean = 13.5 mb) over the 50-y

254   period (Figure 4). Consistent data across the study period for wind speed, atmospheric

255   humidity, and net radiation are not available for this locale.

256

257   *3.2 Catchment hydrology*

258   Stream discharge partitioned into stormflow and baseflow shows how

259   groundwater dominates the total flow of Augusta Creek; baseflow averaged 78% of the

260   total discharge (Figure 3b). There is no linear trend in total (p = 0.14), stormflow (p =

261   0.91), or baseflow (p = 0.83) discharge over the 50 y. In this catchment, stormflow likely

262   reflects mainly precipitation falling on lakes and wetlands that are contiguous with the

263   stream channels because upland soils are highly permeable and there are few impervious

264   surfaces and little overland runoff from uplands to the streams. This is supported by the

265   comparison of annual stormflow volumes to the annual precipitation falling on

266   contiguous lakes and wetlands: on average, stormflow amounts to 57% (range, 44-73%)

267   of the precipitation with no linear trend over the 50 y (p = 0.09, data not shown). The

268   balance, which equates to a mean of 408 mm y^{-1}, could largely be explained by

269   evapotranspirative losses from the lakes and wetlands. If stormflow originating as

270   overland flow from the uplands were important, the total stormflow volume would

271   exceed the precipitation on lakes and wetlands.

272   Our annual water balances for Augusta Creek resemble earlier estimates

273   calculated by Rheaume (1990) over three representative years (1971, 1977 and 1985),

274   which indicated that 62, 65 and 59%, respectively, of the annual precipitation was

275   returned to the atmosphere as ET, mainly during the growing season (May–Sep),

276   although those estimates included ET from contiguous lakes and wetlands as well as

277   uplands. That study also employed hydrograph separation to estimate that about 75% of

278   the annual stream flow in those years was supported by groundwater discharge; our

279   estimate of mean baseflow contribution over the 50-y period is 78%.

280   Our estimate of ET, based on the difference between precipitation on the upland

281   catchment and baseflow discharge out of the catchment, averaged 563 ± 103 mm y^{-1}

282   (Figure 3c), with no linear trend (p = 0.98). Expressed as a percentage of annual

283   precipitation, ET averaged $59 \pm 6\%$ (Figure 3d), also with no trend over the 50 y (p =

284   0.88). Therefore these data show that ET from upland areas of the Augusta Creek

285   catchment has remained remarkably stable over the past 50 y in spite of large changes in

286   land cover towards less area in annual crops and more in deciduous forest.

287

288   *3.3 ET rates from representative vegetation types*

289   We estimated ET in annual crops and perennial vegetation over the 2009–2014

290   period from high-resolution changes in soil water profiles (Figure 5). Except for 2012,

291   which was a drought year, mean growing season ET rates were 495 ± 48 mm y^{-1} for

292   maize, 524 ± 79 for grasslands (fallow and prairie), and 532 ± 47 for woody vegetation

293   (deciduous forest, shrubland, and poplar). These rates are statistically indistinguishable

294   among vegetation types (p>0.05), further supporting the hypothesis that ET rates are

295   similar among annual crops, perennial grasslands, and forests in the Augusta Creek

296   catchment. These ET observations span years of varying warmth (Figure 4) but show no

297   relationship with mean growing-season temperature.

298   While soil water-based ET rates, excluding the 2012 drought year, are lower than

299   the catchment-based ET rates of 600 ± 59 mm y^{-1} in those years (2009, 2010, 2011, 2013,

300   and 2014 in Figure 3c), the soil water-based ET estimates reflect only the growing

301   seasons. Year-round eddy covariance measurements of water fluxes in maize and

302   grasslands at KBS indicate that about 30% of ET occurs outside the May-Sep growing

303   season (Abraha *et al.,* 2015). Adding 30% to the soil water-based ET rates brings rates

304   for maize, grasslands, and woody vegetation to 643, 681, and 692 mm y^{-1}, respectively,

305   all higher but within 15% of the catchment-based ET measurements over those years.

306

307   **4. Discussion**

308   *4.1 Possible explanations for the stability of ET*

309   There are several possible explanations for the long-term stability of catchment

310   ET that we believe are unlikely. One is that there may not have been sufficient time for

311   hydrologic responses to be detected. While the mean transit time for groundwater

312   movement in this kind of catchment is likely greater than a decade (e.g., Saad, 2008),

313   groundwater discharge rates from an unconfined and connected aquifer system would

314   respond to changing recharge at far faster time scales (McDonnell and Beven, 2014).

315   Succession from grassland to forest can be protracted, but the MIRIS forest cover data

316   indicate that most of the reforestation occurred in the first 14 years of the study period

317   (i.e., 1964–78). Many long-term paired catchment studies have shown that water yield

318   after regrowth of harvested forest tends to approach a stable rate within about 10–25

319   years (Hornbeck *et al.,* 1993; Brown *et al.,* 2013).

14

320   Another possibility is that the degree of land cover change over the study period

321   (27% of the upland catchment abandoned from annual crops and 20% of it becoming

322   reforested; Figure 2) may not be sufficiently large to signal a change in water yield, even

323   if annual crops and perennial vegetation had large differences in ET rates. Again, this is

324   unlikely because long-term paired catchment studies have shown significant change with

325   as little as 20% of the catchment either deforested or afforested (Brown *et al.,* 2005).

326   Also possible is that there are offsetting effects exerted by different land covers in

327   the vicinity (Albertson *et al.,* 2001; van Dijk *et al.*, 2012), but this does not seem likely

328   because adjacent catchments have similar mosaics of land cover, and the entire region has

329   experienced similar changes in vegetation over this time period. Compensating land use

330   changes that result in no net change in ET are also a possibility, such as the changes in

331   crops grown as noted above. However the ET rate of oats that were commonly grown in

332   the 1960s and 1970s is unlikely to differ much from the maize that replaced them (Allen

333   *et al.,* 1998).

334   Over the past 50 y the mean annual air temperature has increased by about 1.14

335   °C (Figure 4), and the frost-free season has become longer by about 9 days (Kunkle,

336   2015). Evapotranspiration could increase with warming if available water were not

337   limiting, other meteorological changes did not offset the temperature effect (McVicar *et*

338   *al.*, 2012b), and the vegetation could remain active over the longer growing season.

339   However, during the growing season when most (~70%) of the ET occurs, available soil

340   water typically becomes limiting to ET (Hamilton *et al.,* 2015). Also, most annual crops

341   and many grasses would senesce before the end of the potential growing season because

342   their development is regulated by degree-days (Parmesan and Hanley, 2015).

343   Extrapolation of observations from small catchments that are entirely covered by

344   one kind of vegetation to complex mixtures of vegetation may not be as straightforward

345   as it would seem. Models of ET and discharge from catchments with mixed land covers

346   has often proven challenging to validate, and a variety of possible reasons have been

347   considered (van Dijk *et al.,* 2012). Methodological issues identified by those authors

348   include uncertainties in land cover, precipitation and discharge data; in the case of the

349   Augusta Creek catchment, however, the precipitation and land cover data are likely to be

350   quite accurate. It is also possible that other catchment climate characteristics that we have

351   not considered are more influential to ET than land cover (e.g., Wilcox and Huang,

352   2010). Physical explanations noted by van Dijk *et al.,* (2012) for poor model performance

353   include recirculation of intercepted rainfall, which tends to be more important in forests,

354   and lateral water redistribution between vegetation types; identifying the potential

355   importance of these physical explanations in the Augusta Creek catchment is beyond the

356   scope of this study.

357   We cannot rule out the possibility that changes in the meteorological drivers of

358   atmospheric water demand (i.e., temperature, net radiation, wind speed, and atmospheric

359   humidity; McVicar *et al.*, 2012a, b) could have offset the effects of land cover changes on

360   ET. The steadily increasing partial pressure of atmospheric carbon dioxide could also

361   have reduced plant transpiration rates, although its effect on ET is most pronounced in

362   warm, highly water-limited (i.e., arid and subarid) regions (Donohue *et al.*, 2013; Yang *et*

363   *al.*, 2016; Trancoso *et al.*, 2017). In any case the offset of land cover effects on ET by

364   these atmospheric changes would be a regional phenomenon contributing to the resilience

365   of catchment ET and discharge.

366

367 *4.2 Conclusion*

368   Evapotranspirative water loss in the upland portion of the Augusta Creek

369 catchment has been remarkably resilient across a 50-y period of decreasing cropland,

370 increasing perennial vegetation cover, and warming temperatures, leaving a relatively

371 consistent proportion of precipitation for groundwater recharge and streamflow. Our ET

372 estimates based on catchment water balances compare well with direct measurements in

373 the same catchment since 2009 based on soil water monitoring by time-domain

374 reflectometry for grasslands, annual crops, and perennial bioenergy crops and forest.

375 These observations suggest that water use by rainfed annual crops and perennial

376 vegetation is similar in this setting, and that in humid catchments with soil permeability

377 little affected by land cover, catchment water balances are not likely to be very sensitive

378 to near-term future changes in land cover and climate as long as the land is vegetated, and

379 crops are not irrigated. One such land cover change could be an increase in the cultivation

380 of perennial herbaceous crops for biofuel production, which, based on our findings, does

381 not seem likely to alter catchment water balances in this kind of setting.

382

383 **Figures:**

384 **Figure 1.** Location of Augusta Creek in Michigan (inset) and catchment boundaries

385   (shaded). Precipitation measurement sites are shown by triangles. The catchment

386   boundaries can be viewed in Google Earth: (catchment boundary kml file here).

387 **Figure 2.** Land cover change in the Augusta Creek catchment. Estimates are based on

388   analysis of aerial photos (1960) or satellite imagery (2014 Cropland Data Layer:

389   http://nassgeodata.gmu.edu/CropScape/).

390 **Figure 3.** Precipitation, stream discharge, and evapotranspiration (ET). Panels show

391   annual (Oct-Sep) values of (a) precipitation measured at 3-6 stations (mean = blue

392   line); (b) stream discharge partitioned into baseflow and stormflow; (c)

393   evapotranspiration (ET) estimated as the difference between precipitation and

394   baseflow discharge; and (d) ET as a percentage of annual precipitation. Horizontal

395   lines show the means.

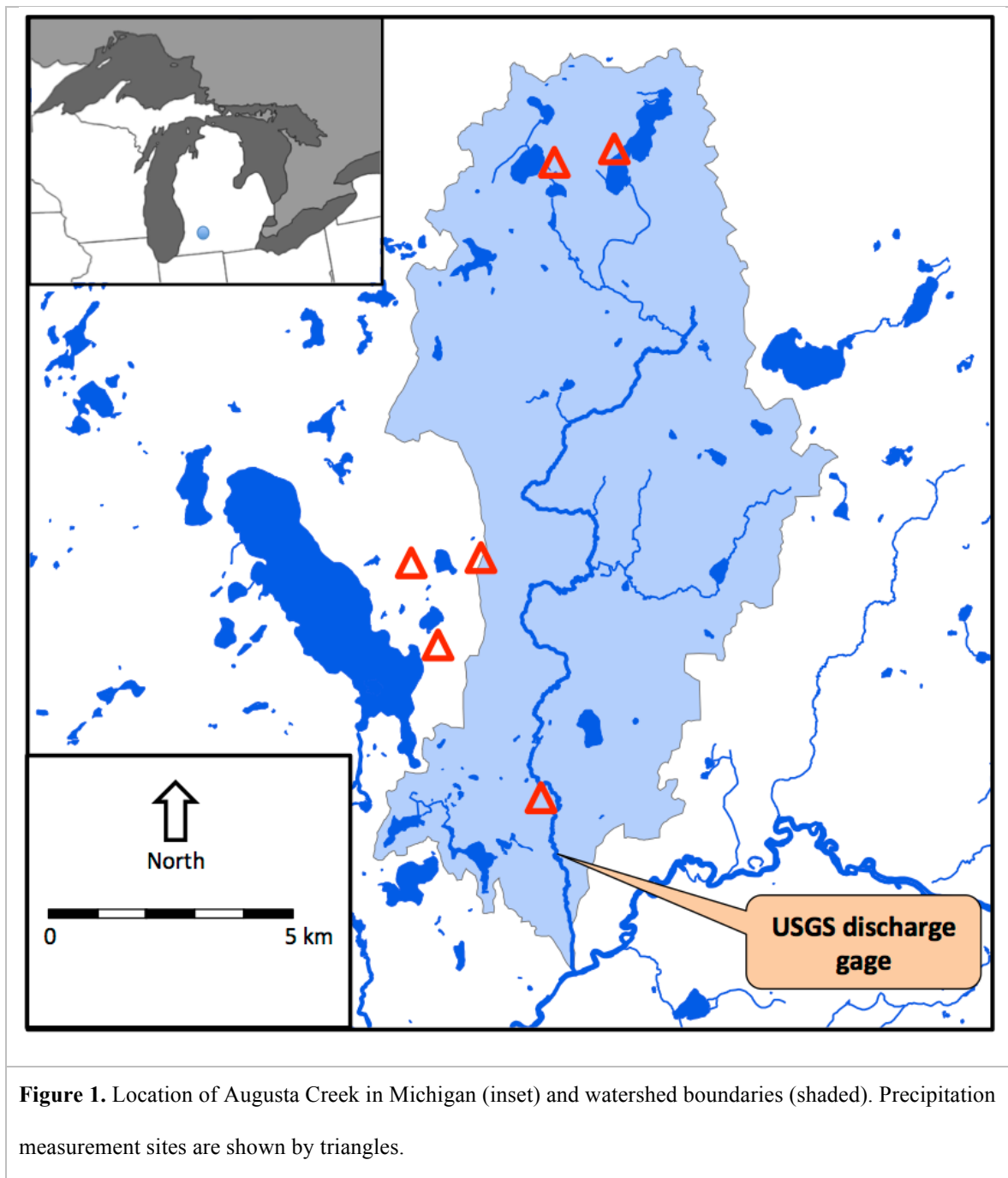396 **Figure 4.** Air temperature for the Augusta Creek catchment, derived from the Midwest

397   Regional Climate Center database (http://mrcc.isws.illinois.edu/). The positive
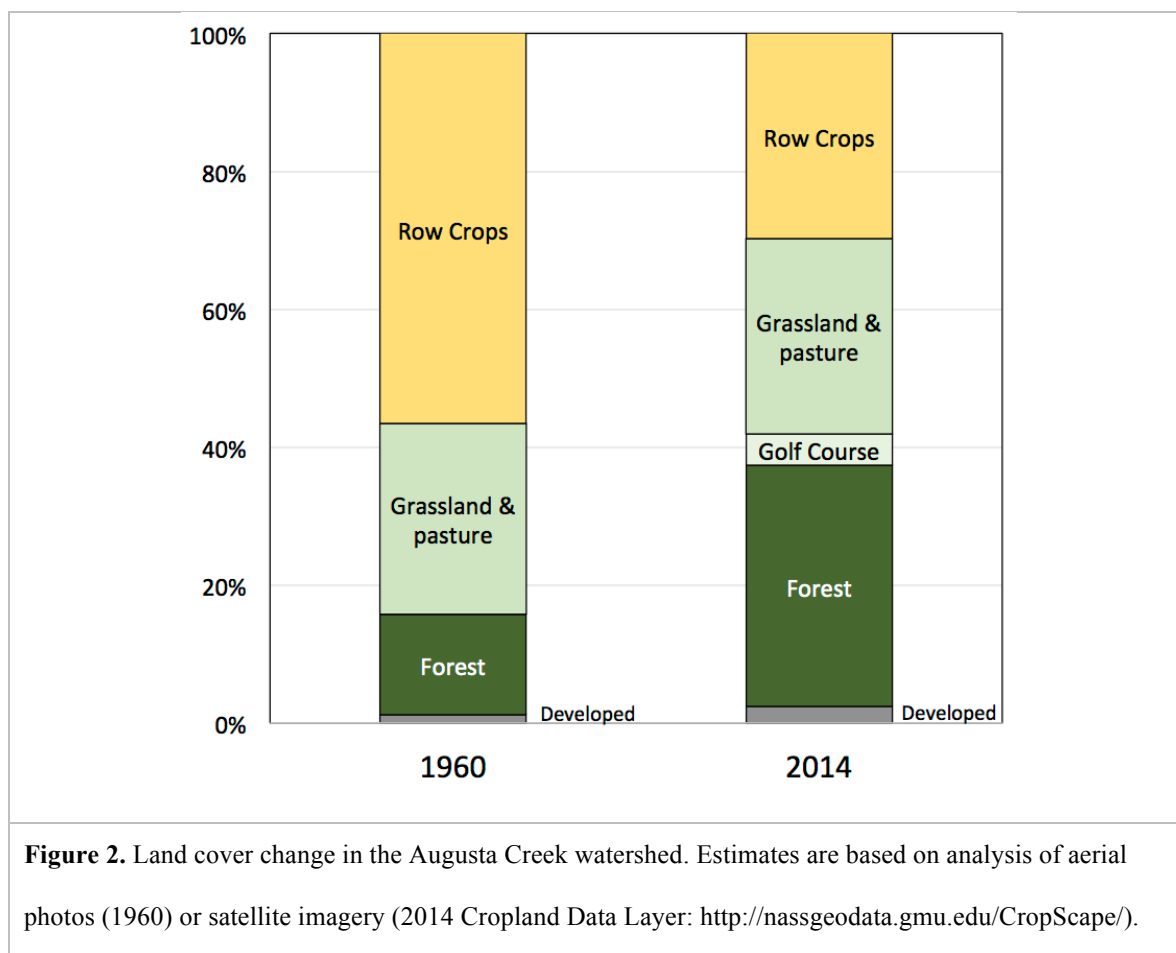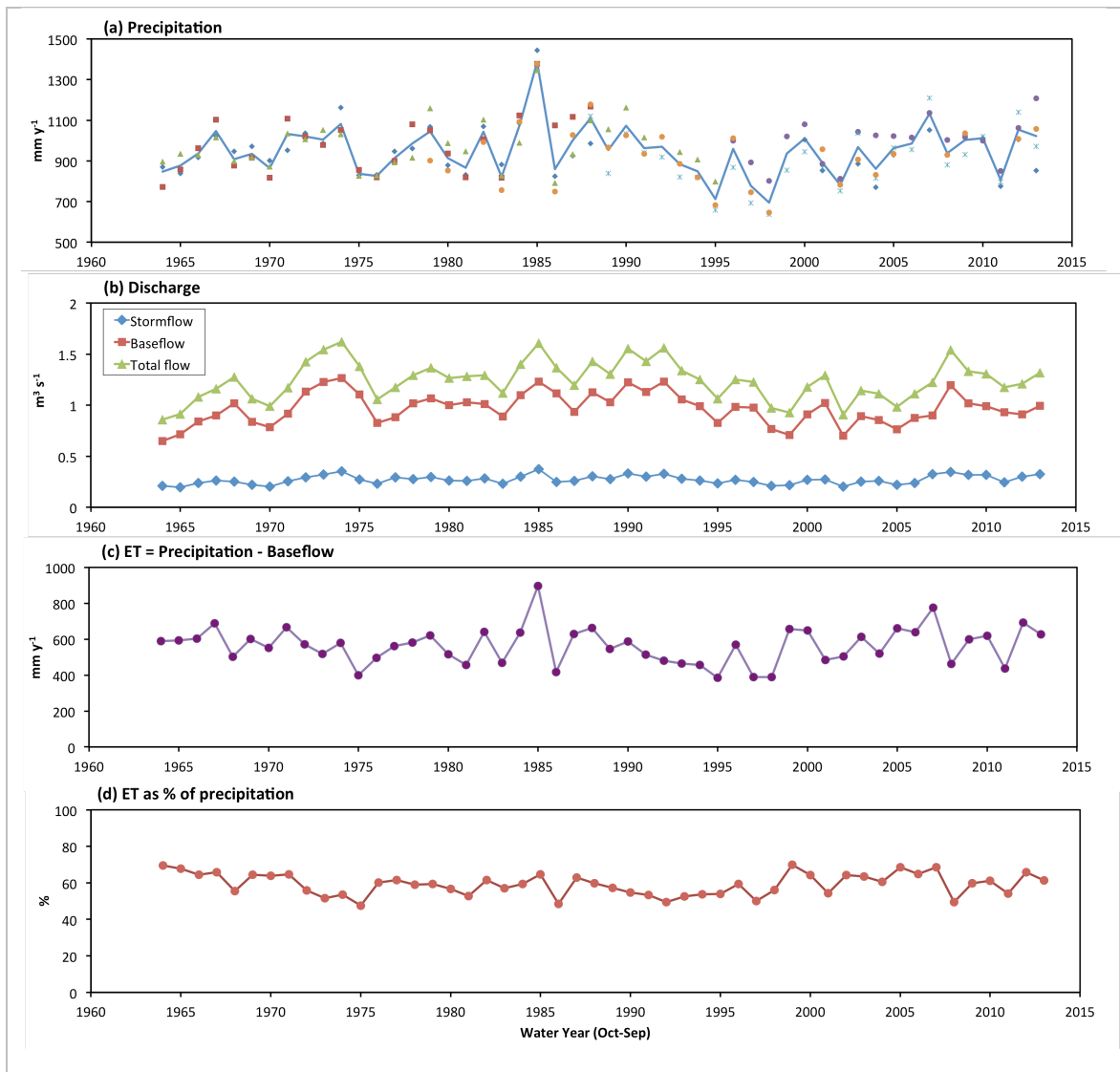
398   change is significant (P = 0.005) and amounts to 1.14°C over the 50 y.

399 **Figure 5.** Rainfall (blue) and evapotranspiration over the growing season (2009-14) from

400   annual maize and herbaceous and perennial vegetation, estimated from continuous

401   observations of plant water uptake in soil profiles.

402

403

Figure 1. Location of Augusta Creek in Michigan (inset) and watershed boundaries (shaded). Precipitation measurement sites are shown by triangles.

Figure 2. Land cover change in the Augusta Creek watershed. Estimates are based on analysis of aerial photos (1960) or satellite imagery (2014 Cropland Data Layer: http://nassgeodata.gmu.edu/CropScape/).

Figure 3. Precipitation, stream discharge, and evapotranspiration (ET). Panels show annual (Oct-Sep) values of (a) precipitation measured at 3-6 stations (mean = blue line); (b) stream discharge partitioned into baseflow and stormflow; (c) evapotranspiration (ET) estimated as the difference between precipitation and baseflow discharge; and (d) ET as a percentage of annual precipitation.
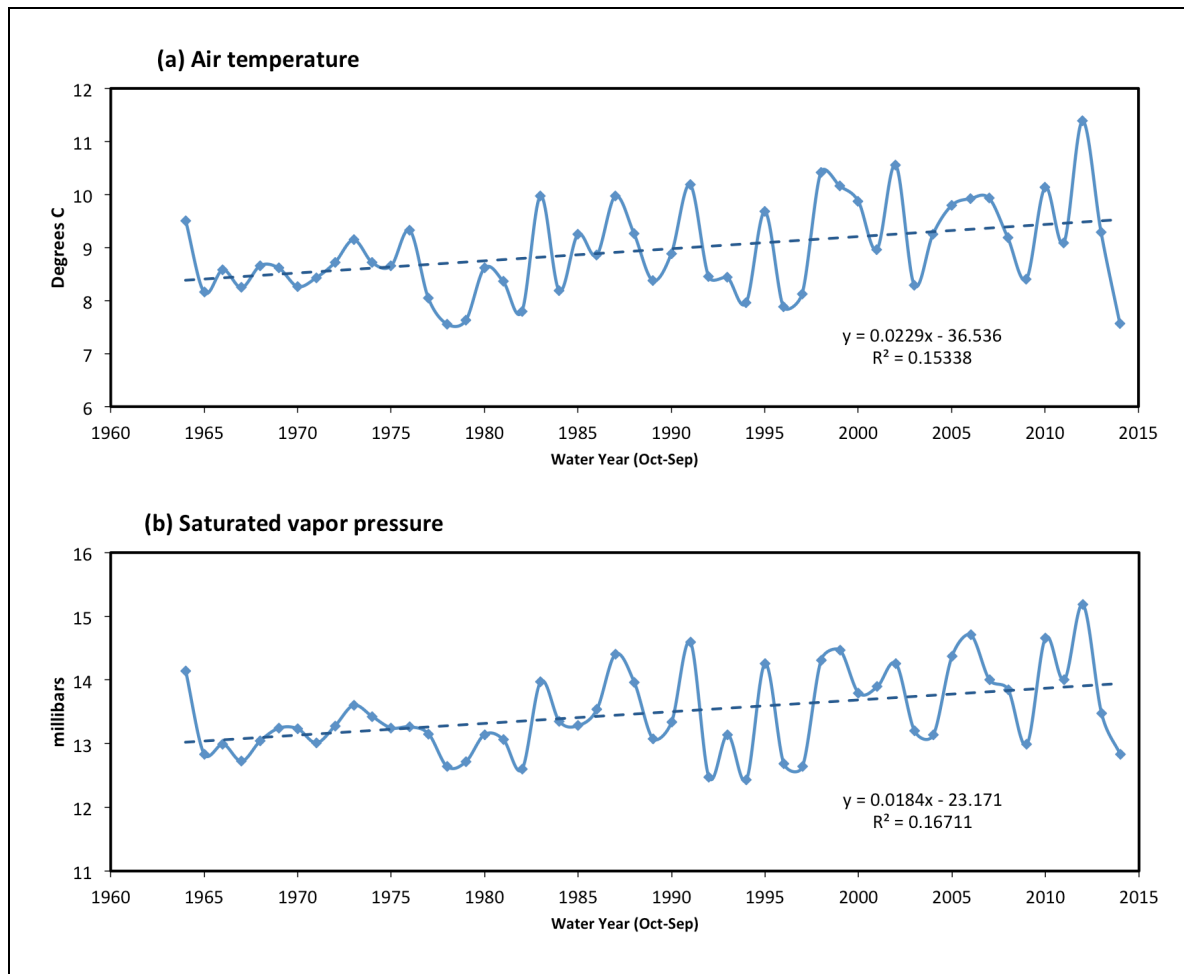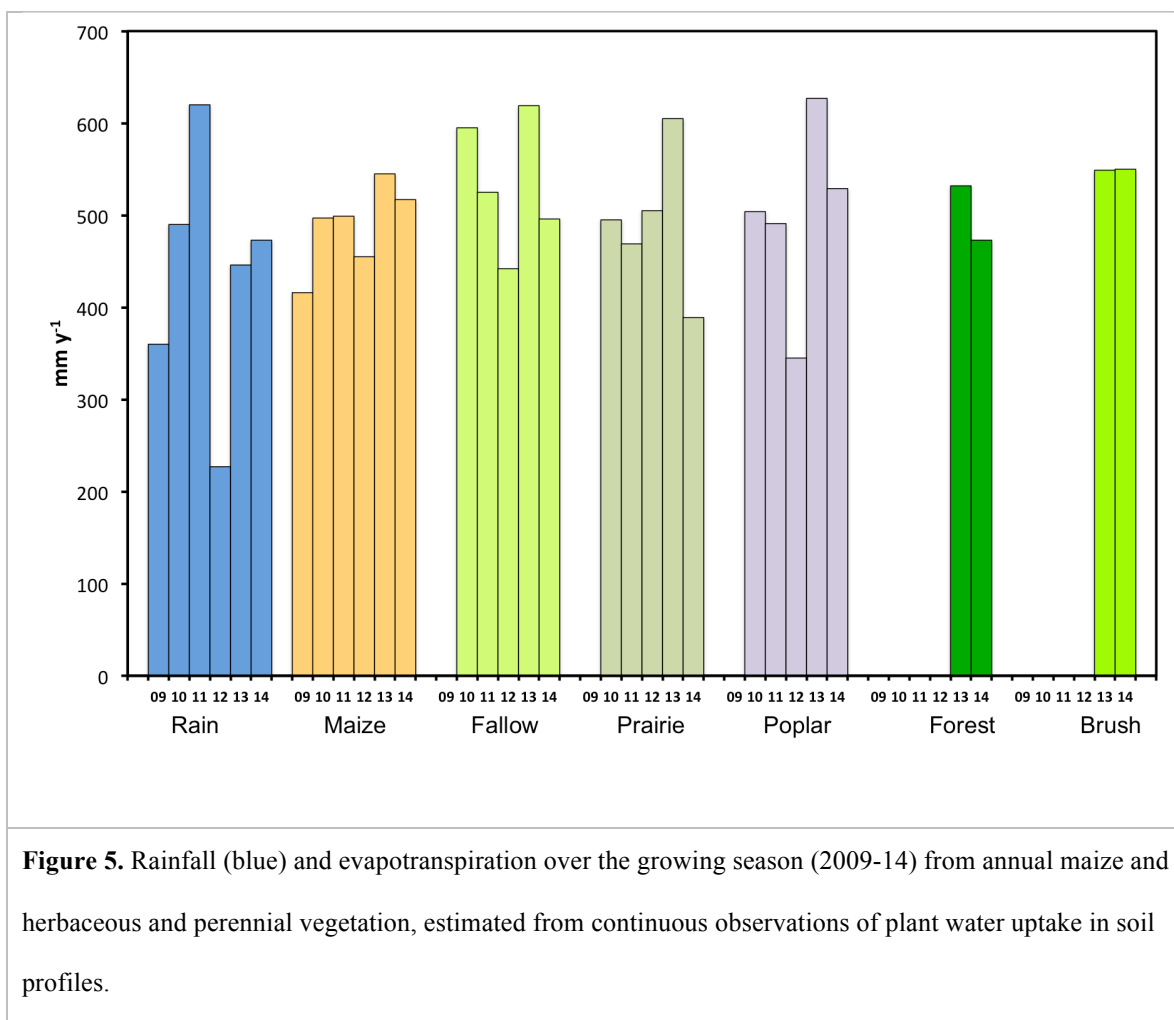
(a) Air temperature

$y = 0.0229x - 36.536$
$R^2 = 0.15338$

(b) Saturated vapor pressure

$y = 0.0184x - 23.171$
$R^2 = 0.16711$

Figure 4. Air temperature (a) and saturated vapor pressure (b) for the Augusta Creek

watershed, derived from the Midwest Regional Climate Center database

(http://mrcc.isws.illinois.edu/). The positive changes are significant (P = 0.005 and 0.003

for temperature and vapor pressure, respectively) and amount to 1.14°C and 0.90

millibars over the 50 years.
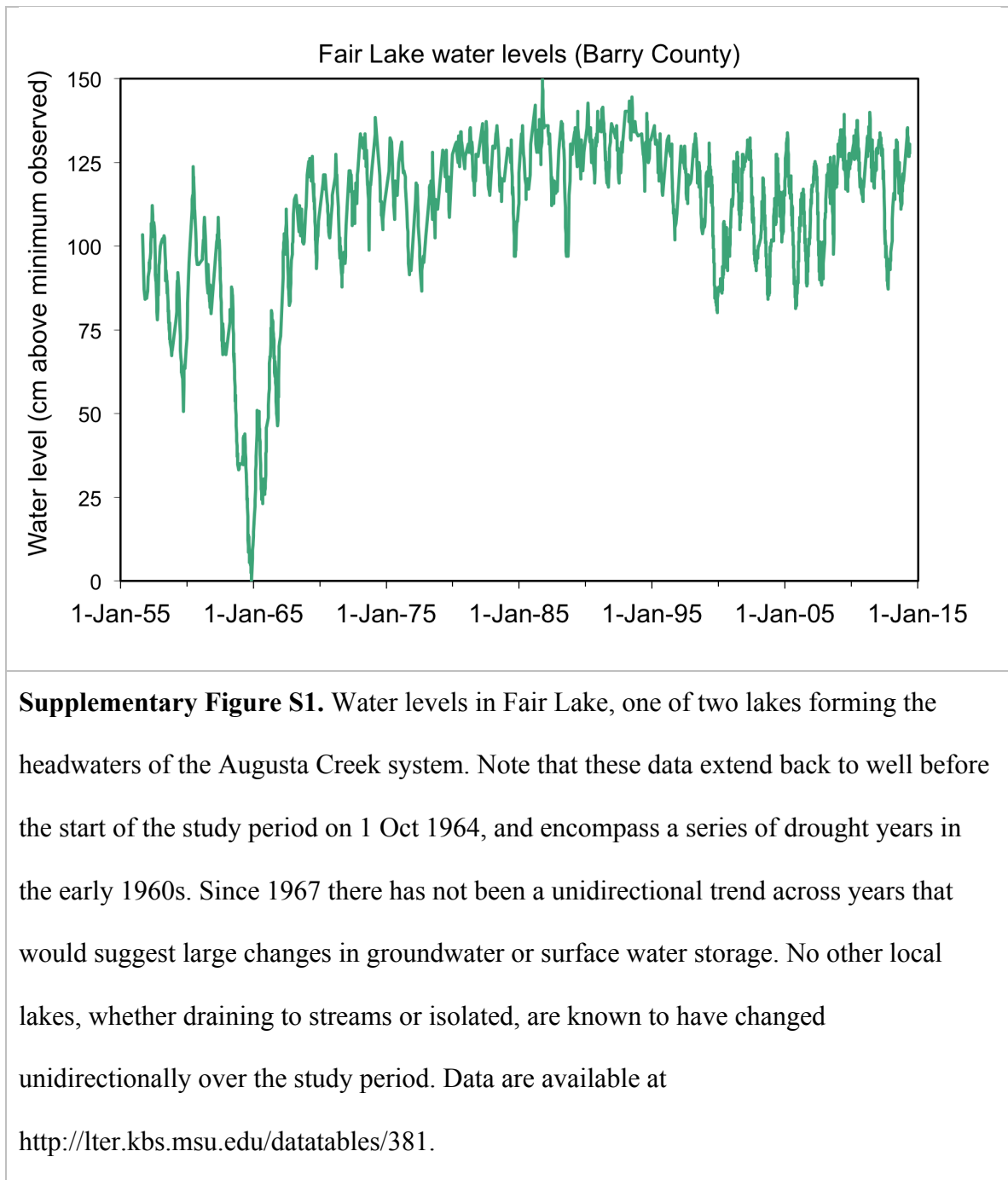
Figure 5. Rainfall (blue) and evapotranspiration over the growing season (2009-14) from annual maize and herbaceous and perennial vegetation, estimated from continuous observations of plant water uptake in soil profiles.

404　**Supplementary figures:**

405　**Supplementary Figure S1.** Water levels in Fair Lake, one of two lakes forming the

406　　　　headwaters of the Augusta Creek system. Note that these data extend back to well

407　　　　before the start of the study period on 1 Oct 1964, and encompass a series of

408　　　　drought years in the early 1960s. Since 1967 there has not been a unidirectional

409　　　　trend across years that would suggest large changes in groundwater or surface

410　　　　water storage. No other local lakes, whether draining to streams or isolated, are

411　　　　known to have had their water levels change unidirectionally over the study

412　　　　period. Data are from http://lter.kbs.msu.edu/datatables/381.
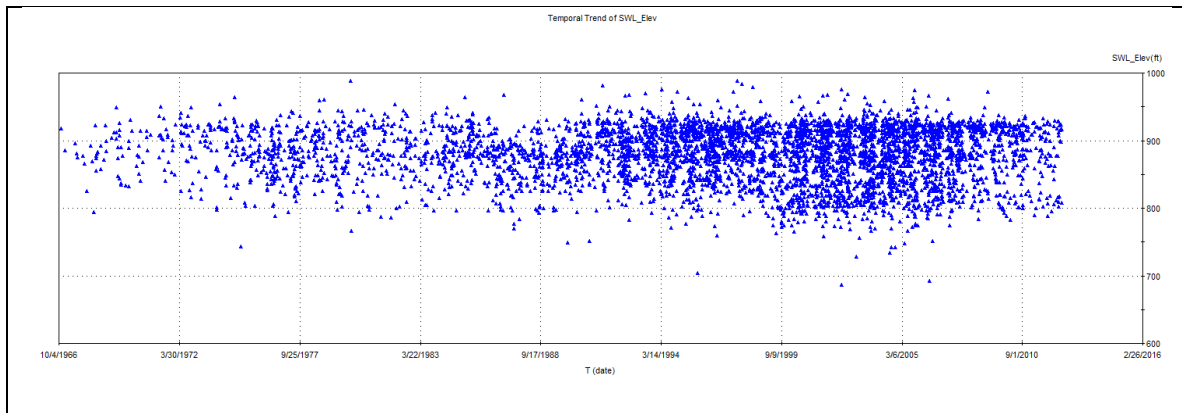
413　**Supplementary Figure S2.** Static water levels measured upon installation of residential

414　　　　water supply wells in the vicinity of the Augusta Creek catchment. Data compiled

415　　　　from public records by Shu-Guang Li of Michigan State University.

416　**Supplementary Figure S3.** The Palmer Drought Severity Index (a) and the Palmer

417　　　　Hydrological Drought Index (b) for the region encompassing the Augusta Creek

418　　　　watershed, derived from the Midwest Regional Climate Center database

419　　　　(http://mrcc.isws.illinois.edu/). There is no significant linear trend in either index

420　　　　($p = 0.34$ and 067, respectively).

421

422

1   **Evapotranspiration is resilient in the face of land cover and climate change in a**

2   **humid temperate catchment**

3

4   **Supplementary Information**

Supplementary Figure S1. Water levels in Fair Lake, one of two lakes forming the headwaters of the Augusta Creek system. Note that these data extend back to well before the start of the study period on 1 Oct 1964, and encompass a series of drought years in the early 1960s. Since 1967 there has not been a unidirectional trend across years that would suggest large changes in groundwater or surface water storage. No other local lakes, whether draining to streams or isolated, are known to have changed unidirectionally over the study period. Data are available at http://lter.kbs.msu.edu/datatables/381.

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Supplementary Figure S2. Static water levels measured upon installation of residential water supply wells in the vicinity of the Augusta Creek watershed. Data compiled from public records by Shu-Guang Li of Michigan State University.

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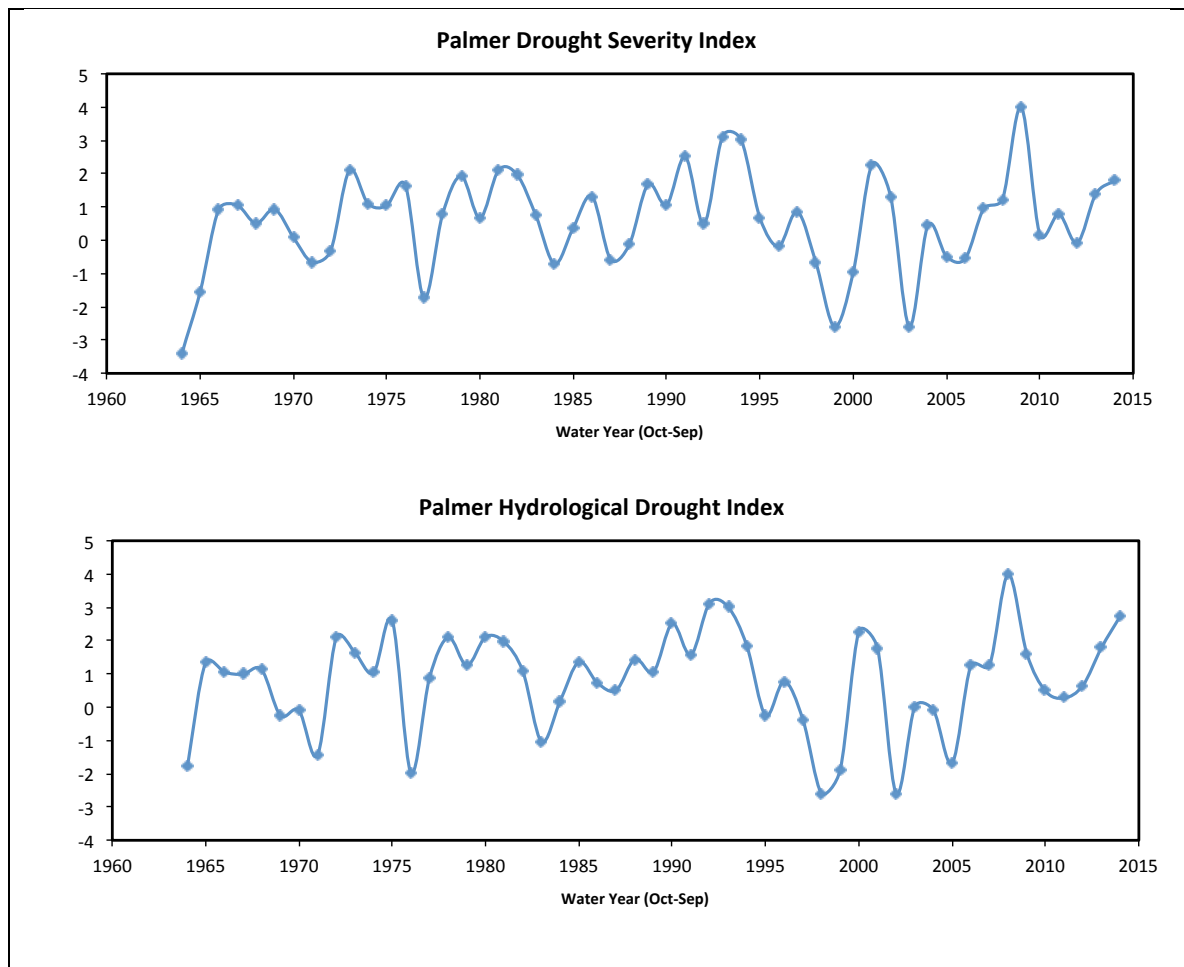
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0.34 and 067, respectively).

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Acknowledgments

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