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Multimethod assessment of evapotranspiration shifts due to non-irrigated agricultural development in Sweden

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SUMMARY

During the 20th century, Sweden underwent a persistent agricultural development. In this study, we use and combine historical hydroclimatic and agricultural data to investigate how this large scale change of land use, and subsequent intensification of crop production, affected regional hydrology in two adjacent Swedish drainage basins. We find a main increase of evapotranspiration (ET) as cultivated area and/or crop production increased during the period 1901–1940. Thereafter, ET stabilized at a new higher level. Comparison between the data given, water balance constrained ET quantification (ET_{wb}), and a range of different comparative estimates of purely climate driven ET (ET_{clim}) shows that only 31% of the steep 1901–1940 increase of ET_{wb} can be explained by climate change alone. The remaining 69% of this ET_{wb} shift, which occurred in both investigated drainage basins, is instead explainable to large degree by the regional land use conversion from seminatural grasslands to cultivated land and associated enhanced productivity of herbaceous species.

1. Introduction

Vegetation interacts dynamically with climate at different scales to regulate water balance and the partitioning of precipitation into evapotranspiration and runoff (Asokan et al., 2010; Destouni et al., 2013; Donohue et al., 2007; Douglas et al., 2006; Gordon et al., 2005; Shibuo et al., 2007). Agricultural development (increase in area and/or production) involves changes of vegetation and consequent biogeophysical land properties such as surface albedo, roughness length, rooting depth and leaf/stem area index, which can all affect the evapotranspiration rate at a given land surface (Kvalevag et al., 2010). Agricultural effects on hydrological flow partitioning depend on factors such as the original, predevelopment coverage of vegetation, the introduced type of agricultural crops, and additionally on whether irrigation is used in the agricultural development.

Land use changes such as deforestation may decrease evapotranspiration and increase runoff, while establishment of forest on sparsely vegetated land may have an opposite effect (Gordon et al., 2005; Vanlill et al., 1980). Conversion of unplowed land in natural and/or seminatural conditions into agricultural crops may increase evapotranspiration (Destouni et al., 2013; Loarie et al., 2011), but under some conditions may decrease it (Schilling et al., 2008), while a change from agriculture to forests by cultivation abandonment may initially decrease evapotranspiration (Qiu et al., 2011) and later increase it (Donohue et al., 2007). In general, the dynamics of agricultural development and its impacts on the hydrological cycle need to be understood under a variety of land use, climate and hydrological catchment conditions (Destouni et al., 2013).

It is then difficult to separate the impact of land use changes from those of climatic change on hydrological flow partitioning, since many climatic and biogeophysical parameters combine to affect the rates of evapotranspiration. The capability of distinguishing the effects of different drivers depends on available data and the development of different methods to interpret them for such distinction (e.g., Destouni et al., 2010a, 2013; Shibuo et al., 2007; Tomer and Schilling, 2009; Wang and Hejazi, 2011). Methodological development is important for understanding the different change drivers and their impacts in the past, as well as for accurately projecting impacts in the future and applying appropriate management measures for society's adaptation to them (Jarsjö et al., 2012). Recent technology such as MODIS (King et al., 1992) and other satellite imagery products (Zhang et al., 2010) have provided new tools for such separation, but only for studying relatively recent time periods that overlap with the accessibility to these technologies (e.g., Cheng et al., 2011; Douglas et al., 2006;

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Loarie et al., 2011). For earlier times, the study of historical land use and associated evapotranspiration changes can for instance be approached by a catchment wise water balance assessment depending on the availability of hydroclimatic and land use data (Asokan et al., 2010; Destouni et al., 2010a, 2013; Shibuo et al., 2007). Furthermore, remote sensing and basin wise assessment of water balance changes can also be fruitfully combined to distinguish water storage changes as additional components of total hydrological change (Karlsson et al., 2012).

In previous studies of hydroclimatic change due to agricultural developments, great emphasis has been put on irrigation, which has been shown to impact climate change in addition to water resources (Bonfils and Lobell, 2007; Boucher et al., 2004; Destouni et al., 2010a; Kueppers et al., 2007; Lobell et al., 2009). However, also non-irrigated agriculture has recently been shown to have similar change impacts on evapotranspiration and thus hydrological flow partitioning, with important global implications (Destouni et al., 2013), not least in view of rising food demands due to the world's growing population (Gordon et al., 2003). Testing and quantifying possible impacts of non-irrigated agriculture, which is much more common worldwide than irrigated agriculture, should then be a priority for hydrological research across a variety of different regions.

In the present study, we investigate effects of non-irrigated agriculture on evapotranspiration and hydrological flow partitioning in two Swedish agricultural drainage basins. For both of these basins, availability of historical hydroclimatic data on temperature, precipitation, wind, lake levels and runoff extends back to the beginning of the 20th century, as does also available information on agriculture (cultivated area and crop yields), which is needed to distinguish the possible agricultural effects on historic hydroclimatic change. As the study seeks to understand these effects on regional water balance and hydrological flow partitioning, it uses a multimethod approach to particularly test and separate the effects of land use change from those of climate change on long term evapotranspiration changes.

2. Study site description

This study uses the hydrologicaly well investigated Swedish Norrström Drainage Basin (NDB) (see, e.g., Destouni and Darracq (2009), Destouni et al. (2010b) and further references therein) as its main case, along with the neighboring Motala Ström Drainage Basin (MSDB) for interbasin comparison (Fig. 1a). Approximately 20% of the Swedish population lives within the NDB area (22 650 km^2) mainly concentrated in the cities of Stockholm, Uppsala, Västeras and Örebro (less than 4% of its area). The basin is also recognized as a hot spot for nutrient loading into the Baltic Sea, due to both its agricultural activity and the size of its population.

About 1300 lakes are spread within the NDB and account for 11% of its total area. Water draining from the NDB flows into the Baltic Sea through four outlets of Lake Mälaren (third largest lake in Sweden, 1078 km^2), three of which are located in the city of Stockholm. Lake Mälaren started to be regulated in 1943 to stop salt water intrusion from the Baltic Sea and to avoid flooding of the Stockholm metropolitan area (Granström, 2003). Its regulation is thus not intended for electricity production or water storage. The other major lake in the NDB, Lake Hjälmaren (fourth largest in Sweden, 477 km^2), drains its waters into Lake Mälaren. Lake Hjälmaren started to be regulated between 1878 and 1888 in order to drain approximately 160 km^2 of land for agricultural use (Norell, 2001).

The elevation of the NDB varies between sea level and 460 m.a.s.l. from south-east to north-west, with land use also changing along this direction. The hills in the north-west of the basin are covered by temperate forest while the center of the basin and the major lake area in the south and east are characterized by open areas comprised mainly of grasslands and agricultural systems. Forests and open areas currently occupy 48% and 36% of the NDB area, respectively. The mean annual precipitation over the 20th century averaged 590 mm/yr as calculated from data by Mitchell and Jones (2005), which is more than double the corresponding mean annual runoff, 227 mm/yr, as calculated from data by the Swedish Meteorological and Hydrological Institute (SMHI, 2010). The basin typically experiences seasonal snowfall during winter that melts and joins the surface runoff during spring.

The neighboring MSDB has similar characteristics as the NDB; it includes a large water body (here the second largest lake in Sweden, Lake Vättern, 3540 km^2) and has similar types of soil, vegetation and historical agricultural development. The 13,283 km^2 of the basin are currently composed of forests (51%) and open land (24%). Most of the agricultural area is in the plains located between Lake Vättern, the Motala Ström River, and the Roxen and Sommen lakes. About 890 surface water bodies in the MSDB account for 22% of its area. Major urban centers include Linköping, Jönköping at the south of Lake Vättern, and Nyköping at the outlet of the Motala Ström River into the Baltic Sea.

The expansion of agriculture in the NDB and MSDB region began in the second half of the 19th century with gradual conversion of original seminatural grasslands to agricultural land (Jansson et al., 2011) (Fig. 1b). The seminatural grasslands located on fertile peat and clay soils were further gradually drained by ditches to expand the plowed land devoted to ley for fodder and cereals (Dahlström et al., 2006). These developments continued until the 1920s when the historical peak of agricultural area was reached. At this time, approximately 20% and 16% of the area of the NDB and MSDB, respectively, was used for agricultural cultivation. From this point to the present, cultivated area has been steadily decreasing accompanied by an increase in forest coverage that, in most cases, arises by natural succession. Even though cultivated area decreased, the crop yields from it continued to increase, mainly due to the introduction of fertilizers and to the abandonment of cereal and ley production rotation (Saifi and Drake, 2008). Currently, crop production in the NDB and MSDB is comprised of cereals (36%), ley (33%), and other crops (31%) such as potatoes, linseed, fodder roots and various types of beans.

3. Materials and methods

In order to distinguish effects of climate and land use changes on hydrological flow partitioning, and more specifically on actual evapotranspiration (AET), we estimated AET by different methods, including a basic, water balance constrained calculation of AET (denoted AET_{wb}) based on the water budget in each basin as given and constrained by the basin data. The AET_{wb} measure includes effects of both climatic and land use change, and its calculation is described further in Section 3.1. Furthermore, we calculated different comparative AET measures with a multimethod assessment approach that uses different combinations of theoretical and empirical climate driven AET models (with results denoted AET_{clim}), in order to distinguish the AET changes driven by climate change alone. Since this comparative multimethod assessment approach (described further in Section 3.2) aimed at distinguishing the effects of only climatic change, all parameters related to land use, such as albedo or plant water availability, were left unchanged through time in all AET_{clim} calculations.

Moreover, by directly comparing change slopes (denoted $sAET_{wb}$ and $sAET_{clim}$) obtained for 20-year moving averages (to filter the large noise of interannual variability) of the different AET