Massive crop expansion threatens agriculture and water sustainability in northwestern China

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Abstract
Northwestern China (NWC) is among the major global hotspots undergoing massive terrestrial water storage (TWS) depletion. Yet driver(s) underlying such region-wide depletion remain controversial, i.e. warming-induced glacier melting versus anthropogenic activities. Reconciling this controversy is the core initial step to guide policymaking to combat the dual challenges in agriculture production and water scarcity in the vastly dry NWC toward sustainable development. Utilizing diverse observations, we found persistent cropland expansion by \( >1.2 \times 10^4 \text{ km}^2 \) since 2003, leading to growth of 59.9% in irrigated area and 19.5% in agricultural water use, despite a steady enhancement in irrigation efficiency. Correspondingly, a substantially faster evapotranspiration (ET) increase occurred in crop expansion areas, whereas precipitation exhibited no long-term trend. Counterfactual analyses suggest that the region-wide TWS depletion is unlikely to have occurred without an increase in crop expansion-driven ET even in the presence of glacier melting. These findings imply that sustainable water management is critically needed to ensure agriculture and water security in NWC.

1. Introduction
The availability of freshwater, vital for supporting agricultural, ecosystem, domestic, and industrial water consumption, is changing across the globe (Vörösmarty et al 2010, Wada et al 2012, Rodell et al 2018, Wang et al 2018). Emerging hotspots of terrestrial water storage (TWS) decline have been identified, triggered by changes in climate and/or anthropogenic activities (Rodell et al 2018, Yuan et al 2019). TWS decline can be particularly acute in arid and semi-arid regions (Taylor et al 2013, Rodell et al 2018), where agricultural production relies predominantly on irrigation from available freshwater storage rather than rainfall (Scanlon et al 2012, Wada et al 2012, Wang et al 2012). Persistent TWS decline superposed with potentially longer and more severe droughts (Held and Soden 2006, Trenberth et al 2014, Huang et al 2016) and slower TWS renewal rate in these regions can pose great challenges to regional water security and food production (Famiglietti et al 2011, Scanlon et al 2012, Famiglietti 2014, Chang et al 2020), thus hampering progress toward achieving the UN Sustainable Development Goals (SDGs) (2015).

Northwestern China (NWC) is among the major hotspots that have been suffering from massive TWS decline (figure 1(a)), detected by the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) satellite gravity
observations (Cao et al 2015, Rodell et al 2018, Xu et al 2019). Numerous studies have been devoted to unveiling the mechanisms behind TWS declines worldwide; however, such driver(s) in the vastly dry NWC remain highly elusive (Rodell et al 2018). Disentangling the primary driver(s) underlying TWS decline in NWC is both essential and urgent because of the dual challenges in the heightened agriculture demand and elevated water scarcity in this region. Such effort is the core initial step to properly guide policy development toward achieving SDGs.

In NWC, the agricultural water use, primarily via irrigation, accounts for >85% of the total water use among all sectors (figure S1 available online at stacks.iop.org/ERL/17/034003/mmedia). The greatest irrigation need is from cotton farming (Shen et al 2013), which accounts for ~85% of total cotton production in China (figure S1). Indeed, the water footprint in NWC is identified as being among the largest across the globe (Gleeson et al 2012). Furthermore, NWC is a typical dryland system, with annual precipitation generally less than 20 cm yr$^{-1}$, mostly occurring in the summer (figure S2). Potential evapotranspiration (PET) is approximately tenfold greater than precipitation, i.e. ~250 cm yr$^{-1}$ (figure S2) (Cao et al 2015). Thus, agricultural production in this region relies predominantly on irrigation extracted from surface water and groundwater, which is originally recharged from glacier melt from the Tien Shan mountains (NWC sits within Asia’s ‘water tower’) (Immerzeel and Bierkens 2012, Gardner et al 2013, Farinotti et al 2015). Many studies have shown that glaciers in the High Mountain Asia, including Tien Shan, have lost area and mass in the recent years, which has substantially contributed to the increased river runoff (Farinotti et al 2015, Brun et al 2017). However, if the shrinkage of the Tien Shan glaciers continues, such contribution will eventually decline after reaching the peak glacier melt (i.e. ‘ tipping point’), which is likely to occur in a few decades (Duethmann et al 2016, Huss and Hock 2018). The consequences will be a reduction in the future water supply if precipitation does not increase enough to compensate for the water shortage, thus impairing crop production and further socioeconomic development in NWC (Sorg et al 2012, Bolch 2017). In addition, the NWC dryland is likely to suffer from more severe droughts in the future (i.e. greater drought-prone areas, longer drought duration, and stronger drought severity) (Huang et al 2016, Su et al 2018, Li et al 2020). This will in turn increase the irrigation demand for sustaining agricultural production and exert a heavier reliance on freshwater extraction, making TWS increasingly unsustainable.

Some studies have attributed the TWS decline to the warming-induced glacier melting (Xu et al 2019, Yuan et al 2019). However, glacier melting alone cannot explain the region-wide huge freshwater loss, as the observed TWS decline trend ($-8.33 \pm 2.03 \text{ Gt yr}^{-1}$ for a region of $\sim 2031 \text{ km}^2$) (figure 1(a)) is much larger than the reported glacier melting rate ($-5.4 \pm 2.8 \text{ Gt yr}^{-1}$) (Farinotti et al 2015) or the river runoff ($-4.4 \pm 1.19 \text{ Gt yr}^{-1}$) (Shean et al 2020). More importantly, even though the glacier melting may contribute to the TWS decline in mountainous areas (figures 1(a) and S3), the loss of glacier should not break topographic barriers, as NWC sits within an endorheic basin. Consequently, there should have been a TWS increase in the lowland if other water inflows/outflows remained stable, which however contradicts the observed region-wide TWS depletion including the lowland (figure 1(a)). Therefore, other driver(s) must exist to explain the pathways of the ultimate freshwater loss. Surface-water diversion for supporting irrigated agriculture has been proposed as a potential alternative cause (Rodell et al 2018), but direct evidence for such hypothesis is still lacking. Clarifying the exact driver(s) is core to demonstrate the consequence of anthropogenic activities on water and agriculture sustainability in this vastly dry yet under-studied region.

To achieve this goal, here we harness a diverse suite of independent datasets, including GRACE/GRACE-FO (denoted as GRACE hereafter) TWS, satellite-based land use and land cover products, climate observations, as well as agricultural production and water use statistics from the Chinese statistical yearbook (section 2). The major contribution of this study is to provide direct evidence to elucidate the causal linkages among crop expansion, irrigation, evaporative water loss (activities occurring at the local scale), and the region-wide TWS depletion (a phenomenon at the regional scale). Once the mechanism of the TWS depletion is identified by converging evidence from multiple independent datasets, we could gain confidence in the pathways of the ultimate freshwater loss in recent years, which will inform policy making toward achieving SDGs in NWC.

2. Materials and method

2.1. TWS data

TWS data came from GRACE level 3 RL06 (version 2) data provided by JPL (https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/). Here, JPL data were used for its unique characteristic that each 3° mascon element is relatively uncorrelated with neighboring elements (Rodell et al 2018). The data provide gridded global water storage/height anomalies relative to the 2004–2009 time mean, as well as scaled uncertainty estimates. Our analyses relied on the monthly mascon data (available from 2002 April to 2019 December) at a spatial resolution of 3° (but represented on 0.5° grids). The long-term trend calculation started from 2003 as it is the first complete year in the GRACE era (only 9 months of data in 2002). There are some gaps in the
GRACE series, including an about 1 year gap between GRACE and GRACE-FO, which are not expected to affect our trend calculation. Detailed data characteristics and potential uncertainties are provided in table S1.

2.2. Precipitation, evapotranspiration (ET), potential ET (PET), and runoff
We used monthly accumulated precipitation observations from two different datasets: Tropical Rainfall Measuring Mission (TRMM) 3B43 (available from 2002 April to 2019 September, the spatial resolution is 0.25°) (https://gpm.nasa.gov/missions/trmm), and ERA-Interim provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (available from 2002 April to 2019 August, the spatial resolution is 0.5°). The precipitation data from the two different datasets may have different characteristics and potential uncertainties. To achieve this, we employed a parsimonious water balance equation (1) to (a) establish the ‘factual’ scenario (i.e. what GRACE TWS observes given the actual ET) as the baseline, and (b) simulate the ‘counterfactual’ TWS as if an increase in ET in crop expansion area had not occurred:

\[ dS_t = S_t - S_0 = \sum_{i=1}^{t} (P_t - ET_t - Q_t + \varepsilon_i), \]

where \( dS_t \) is the TWS change in the \( t \)th month since the first time step (i.e. 2003 January); \( S_t \) is the TWS in the \( t \)th month; \( S_0 \) is the TWS in the first time step, the range of \( t \) is from 0 (2003 January) to 143 (2014 December), and as in this period all the three hydrological components (i.e. TRMM precipitation, GLEAM ET, and GRUN runoff) are concurrently available. \( P_t \), \( ET_t \), \( Q_t \), and \( \varepsilon_i \) represent precipitation, ET, runoff, and the residual term in the \( t \)th month, respectively. The effect of irrigation, although it did not explicitly appear in equation (1) as irrigation is a lateral water flow internal within the NWC, has been implicitly accounted for by ET, whose enhancement was supplied by irrigated water. Note that the values of all terms in equation (1) are the domain-average across the entire NWC.

2.6. National statistics
Statistical data including the cropland area, irrigated area, crop types, grain production, water usage, and supply were obtained from the Chinese annual statistical yearbook (https://data.stats.gov.cn/english/easyquery.htm?cn=E0103). Definitions for these variables can be found in supplementary text S1.

2.7. Statistical analyses
We used the Sen’s slope method to evaluate the secular trend of TWS and other variables. The monthly values (or anomaly) of each variable were first aggregated for each year (or for growing season), and then their trends were calculated based on the annual (or growing-season) mean using Sen’s slope. All trend significance testing is based on a non-parametric Mann–Kendall test with \( \alpha \) equal to 0.05.

2.8. Counterfactual analyses
To quantify the exact impact of the irrigation enhancement-induced in evaporative water loss on the TWS trajectory, we conducted counterfactual analyses. To achieve this, we employed a parsimonious water balance equation (1) to (a) establish the ‘factual’ scenario (i.e. what GRACE TWS observes given the actual ET) as the baseline, and (b) simulate the ‘counterfactual’ TWS as if an increase in ET in crop expansion area had not occurred:

\[ dS_t = S_t - S_0 = \sum_{i=1}^{t} (P_t - ET_t - Q_t + \varepsilon_i), \]

where \( dS_t \) is the TWS change in the \( t \)th month since the first time step (i.e. 2003 January); similarly, \( S_t \) is the TWS in the \( t \)th month; \( S_0 \) is the TWS in the first time step, the range of \( t \) is from 0 (2003 January) to 143 (2014 December), and as in this period all the three hydrological components (i.e. TRMM precipitation, GLEAM ET, and GRUN runoff) are concurrently available. \( P_t \), \( ET_t \), \( Q_t \), and \( \varepsilon_i \) represent precipitation, ET, runoff, and the residual term in the \( t \)th month, respectively. The effect of irrigation, although it did not explicitly appear in equation (1) as irrigation is a lateral water flow internal within the NWC, has been implicitly accounted for by ET, whose enhancement was supplied by irrigated water. Note that the values of all terms in equation (1) are the domain-average across the entire NWC.

Our counterfactual analysis requires multiple data sources, i.e. precipitation, ET, PET, runoff, and.
TWS, which have different temporal coverage, spatial resolution, and sources of uncertainties (summarized in table S1). To minimize the potential confounding impact of such inconsistency in our findings and interpretation, we took several measures to ensure the validity of our results. First, we constrained our counterfactual analysis only to the overlapping periods across all datasets, i.e. 2003 January to 2014 December. This is also the main period during which NWC suffered from TWS depletion, and therefore is representative of our entire study period. To reduce the potential biases related to different spatial resolutions, the analysis was established on spatially averaged values across the entire NWC. To mitigate the impact from different sources of data uncertainties, we introduced an instantaneous residual term to achieve the ‘closure’ of the TWS balance between GRACE observations and that derived from equation (1) with GLEAM ET, TRMM precipitation, and GRUN runoff. This parsimonious approach provides a first-order baseline for our counterfactual analyses. Introducing this residual term here is necessary given the widely known uncertainties of individual data sources (Miralles et al. 2011, Long et al. 2014, Ghiggi et al. 2019) that propagated into the water balance equation and consequently resulted in TWS imbalance (figure S8).

For the counterfactual analyses, we removed the long-term ET trends for each 0.25° GLEAM grid (separately for each month) that has undergone crop expansion (i.e. with a crop coverage change > 0) and exhibiting a significant long-term trend of ET ($p < 0.05$) in a certain month. The 95% confidence interval of the slope was calculated as the uncertainty bounds (figure S9). The de-trended ET was substituted into equation (1) to obtain the change in counterfactual TWS, with all other terms unchanged.

3. Results

3.1. Secular depletion of TWS in NWC

GRACE mascon solutions (JPL RL06 version 2, section 2) reveal a long-term declining trend of TWS in NWC from 2003–2019, at a rate of $-0.41 \pm 0.10$ cm yr$^{-1}$ ($p < 0.05$) (figure 1). The overall spatial pattern is consistent with previous studies, albeit a different trend in magnitude from Rodell et al. (2018), i.e. $-2.56 \pm 0.23$ cm yr$^{-1}$ from 2002–2016. This is because the latter was restricted to a much smaller domain, i.e. the mountainous region (i.e. Tien Shan) with the severest TWS depletion rate. The TWS trend in NWC largely exceeded the inter-annual variability in TWS, according to the trend to variability ratio analysis (Vishwakarma et al. 2021). The risk of freshwater depletion in NWC is comparable to other hotspots in China, i.e. North China Plain (NCP) and southern Tibetan Plateau (STP) (figure 1(a)), where ultimate causes have been extensively studied and confirmed with high confidence (Rodell et al. 2018, Xu et al. 2019, Chang et al. 2020). Accordingly, tailored agricultural and water provision policies have been rolled out in these regions (Zheng et al. 2010). In contrast, the ultimate cause in NWC remains controversial and unconfirmed.

3.2. Concurrent crop expansion and growth in irrigation demand

Corresponding to the massive TWS depletion, we observed a substantial increase in agricultural water use during the same period (figure 2). In fact, NWC is a hotspot that has undergone the most prevalent cropland expansion in China from 2002–2015 (figure 2(a)), consistently revealed by the Chinese statistical yearbook and satellite-based land cover/use

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**Figure 1.** The long-term dynamics of TWS in China from 2003–2019. (a) The long-term linear trend (Sen’s slope) in GRACE TWS. Stipples denote pixels where the TWS trend is significant at the 0.05 level based on the Mann–Kendall test. Underlying drivers for regions with prevalent TWS decrease (synthesized mainly by Rodell et al. (2018)) are shown here for the major hotspots in China: NCP, STP, and NWC. Black line denotes the boundary for NWC. For visualization clarity, regions outside China are displayed with transparency and the trend map is smoothed with a 150 km Gaussian filter (Rodell et al. 2018). All analyses were conducted at the original 3° × 3° resolution of the GRACE mascon. (b) Time series of TWS anomaly over NWC. Shading represents uncertainties (section 2) and the dashed line is the fitted linear trend using least-squares regression ($p < 0.05$). The number $-0.41 \pm 0.10$ cm yr$^{-1}$ is the Sen’s slopes for the region-wide long-term trend in NWC.
Figure 2. Concurrent dynamics of cropland coverage and agricultural water use in NWC. (a) The long-term change in cropland coverage from 2002–2015 in China. (b) The anomaly of cropland area ($\times 10^3$ km$^2$) in NWC. Here, anomalies were calculated as the deviation from the values in 2002 (i.e. the starting year). (c) The grain production ($\times 10^9$ kg) and the anomaly of irrigated area ($\times 10^3$ km$^2$) in NWC. (d) The groundwater supply ($\times 10^9$ m$^3$ yr$^{-1}$) and agricultural water use ($\times 10^9$ m$^3$ yr$^{-1}$) in NWC. The irrigated area, grain production, and water use/supply datasets all come from the statistical yearbook (section 2). (e) The time series of irrigation efficiency (defined as the percentage of water amount used by crops relative to the total water withdrawal, section 2) and agricultural water use per unit of crop area ($\times 10^6$ m$^3$ km$^{-3}$, agricultural water use divided by irrigated area).
Figure 3. Long-term trends in the growing-season (average from May–August) ET and precipitation in NWC from 2003–2018. (a) The long-term linear trend (Sen’s slope) in growing-season ET (calculated based on global land surface evaporation: the Amsterdam methodology (GLEAM) dataset). Stipples denote pixels where the trend is significant at the 0.05 level based on the Mann–Kendall test. (b) Probability frequency of ET trends over pixels undergoing crop expansion (area with a positive cropland coverage change, identified in figure 2(a)) and the rest of NWC. (c) Annual time series of the growing season ET over crop expansion area, the rest of NWC, and the entire NWC. Asterisks indicate that the associated trend is significant. Figures (d)–(f), same as (a)–(c) but for precipitation, calculated based on TRMM.

The cropland expansion in NWC is remarkable considering that most other Chinese regions were witnessing a significant decrease in cropland coverage during the same period, even in the largest crop production zone of wheat and maize in China (i.e. NCP) (figure 2(a)). The cropland expansion in NWC has led to an increase in irrigated area (from 30 540–48 830 km$^2$, equivalent to a 59.9% increase) in support of grain production (figure 2(c)). This caused a huge rise in water demand, evidenced by a 19.5% increase in agricultural water use (from $4.57–5.46 \times 10^{10}$ m$^3$ yr$^{-1}$ between 2004 and 2015, figure 2(d)), even though the water use per unit of crop area has been decreasing concurrently, due to a steady increase in irrigation efficiency (from $\sim$40% in 2004 to $\sim$80% in 2018, figure 2(e)). Such an increase in irrigation efficiency is a result of the improvement of the irrigation infrastructure and the installation of water-saving irrigation technologies (e.g. drip irrigation and/or plastic mulching) since the 1990s (Shen et al 2013). Notably, groundwater withdrawal has doubled from $5.8 –12 \times 10^8$ m$^3$ yr$^{-1}$ between 2004 and 2015 (figure 2(d)). In more recent years, we found a decrease in both agricultural water use and groundwater withdrawal (figure 2(d)). Such a decline, consistent with the decrease in grain production (figure 2(c)), might have contributed to the slight rebound of TWS since 2015 (figure 1(b)). Water use in other sectors, i.e. industrial, domestic, and ecological, only accounts for less than 15% of total water use (figure S1) and is thus unlikely to have contributed to the massive TWS decline.

3.3. Concomitant increase in ET in croplands

These reported increases in agricultural irrigation demand due to cropland expansion and grain production would enhance the growing-season (May–August) ET. In our study domain, the ET can come from agricultural systems, natural ecosystems (mostly in mountainous areas), and deserts. Substantially faster ET increase occurs in agricultural systems, evidenced by satellite-based GLEAM ET estimates, which revealed larger ET trends in areas experiencing massive crop expansion than the rest of NWC (figures 3(a) and (c)). Such a growing trend in ET cannot be explained by growing-season precipitation, which did not exhibit a detectable long-term trend in most of the study domain (except the Tarim basin) during the GRACE era (figures 3(d) and (f)). In addition, there were no significant differences in the growing-season precipitation trend ($p = 0.31$) between areas with and without crop expansion, unlike their distinct contrast in the ET trend (figures 3(b) and (e), figure S4).

Such an enhanced ET in crop expansion area was less likely driven by the differences between atmospheric water demand (i.e. PET) and supply (i.e. precipitation), as no prevalent increase in PET can be
found for areas coinciding with the TWS depletion (figure S5). These findings suggest that the growing-season evaporative water loss is mostly likely driven by cropland expansion to sustain grain production.

3.4. Causal linkage between evaporative water loss and TWS depletion

Is the evaporative water loss due to intensified irrigation and agricultural production the ultimate cause of the observed region-wide TWS depletion? To disentangle this mechanism in the presence of glacier melting, we conducted counterfactual analyses by removing the observed ET trend over the crop expansion area during our study period. Utilizing the water-balance equation (equation (1), section 2), we found that there would have been no significant region-wide TWS decrease as observed by GRACE without an ET increase in the crop expansion area (figure 4). This suggests that the evaporative water loss due to increased irrigation demand, ultimately from crop expansion, is the most plausible driver of the region-wide TWS depletion over NWC, as other water inflow/outflow terms (i.e. precipitation, glacier melting, runoff, etc.) except ET, were kept unchanged between our factual (as observed) and counterfactual scenarios. Note that there appears to be spatial inconsistency between the TWS trend and crop expansion (figures 1 and 2); the primary cause is that the water consumed for irrigation (for supporting crop expansion) does not necessarily originate from local regions, but rather is largely being extracted from the surface/groundwater that comes originally from the Tien Shan glacier melting. Such water movement within NWC, i.e. from the mountainous area to lowlands (where crop area is restricted to and ET enhancement happens), contributed to the observed region-wide TWS depletion.

4. Implications and limitations

4.1. Implications for sustaining water and agriculture security

Our findings imply that the cropland expansion enhanced evaporative loss and the water diversion of surface/groundwater originated from Tian Shan glacier melting to crop regions has substantially escalated the region-wide TWS decline in NWC, threatening the sustainability of both water and agriculture. Continuous demand for growth in agricultural production could further drive the expansion of croplands in the future, which will only exacerbate the already acute TWS depletion. As Tien Shan glaciers are expected to continue retreating under climate change, river runoff will be increasing first but decreasing after a tipping point, as the meltwater from the reduced glaciers can no longer produce as much as before; and this tipping point has been projected to arrive in the next decades, ranging from the 2020s to the middle of the 21st century, depending on the future emission scenarios and characteristics of the glacierized catchments (Huss and Hock 2018). Beyond such point, the availability of freshwater and agricultural productivity in the vast NWC will be on a perilous path. Such a scenario can already be mimicked by episodes of drought, which can diminish the natural water supply for agricultural irrigation (Famiglietti et al 2011, Voss et al 2013, Asoka et al 2017). For example, we found a sharp decrease in precipitation in 2008 (i.e. the driest year since 2003 with annual precipitation less than 15 cm yr$^{-1}$ and persistently high temperature (Cao et al 2015)), despite the absence of the long-term precipitation decline in NWC (figure S6). In this year, a marked TWS anomaly emerged, i.e. 1.49 cm decline from 2007–2008 (figure S7), while agricultural production remained at a steady increase. Notably, such a decrease in TWS storage was not recovered in the subsequent year even though precipitation had returned to normal conditions (figure S7). The reduced natural recharge (together with increased crop evaporative demand under a higher temperature) led to the slow recovery of freshwater storage, and hence increased the susceptibility to drought. This analysis provides a natural experiment to demonstrate the more acute threats to water and food sustainability when glacier meltwater supply reaches the peak and starts to decline in the future, if croplands continue to expand and irrigation demand persists. Such a trajectory is very similar to the perilous path in the Middle East or in the Central Valley in California, where sustainable water management policies have already been enacted (Faunt et al 2016)
Drylands are often considered as potential candidates for cropland expansion, often at the cost of freshwater storage and other environmental consequences (Wang et al. 2012). Historical climate warming (Li et al. 2011, Wang et al. 2013) has intensified irrigation demand (Shen et al. 2013) and water stress in the drylands of NWC. Future irrigation demand might further increase with rising temperature along with projected longer and more severe droughts (Su et al. 2018, Li et al. 2020, Rosa et al. 2020). Projection showed that the irrigation water demand in this region will increase by 4.27–6.15 billion m$^3$ in the next 60 years (Guo and Shen 2016). This increases the increasingly severe water insecurity in NWC and more broadly Central Asia in the context of climate change, and attaches great importance to more sustainable irrigation practices (Deng et al. 2006, Daryanto et al. 2017) along with better water management.

Although water-saving technologies, often promoted and supported by governments in many regions of the world (Grafton et al. 2018) including China, have greatly improved the irrigation efficiency in NWC (Shen et al. 2013), the core conflict still exists between the water demand from the expanded croplands and the insufficient water supply. This is because the crop expansion and production growth far exceeded the rate of irrigation efficiency improvement as shown in this study, a pattern also observed in other regions/countries (Grafton et al. 2018). Furthermore, water-saving technologies could actually adversely impact region-wide TWS, a phenomenon conceptualized as the ‘paradox of irrigation efficiency’, i.e. farm-scale enhancement in irrigation efficiency is unable to improve watershed-scale freshwater availability. This is because these water-saving techniques do not necessarily reduce the total irrigation water use (even though the irrigation efficiency is increased), but the runoff recovered from irrigation can be substantially reduced (aggregated to the regional scale) due to increased irrigation efficiency (occurring at the local scale) (Xiong et al. 2021). This highlights the necessity of region-scale water accounting for mitigating water insecurity (Grafton et al. 2018).

During our study period, NWC has also suffered from other environmental problems such as desertification and land degradation. To combat these problems, a few ecological restoration projects have been launched, e.g. the Grain for Green Program and the Natural Forest Protection Project (Yang et al. 2014). Despite the positive effects on increasing forest fraction (often from grassland) and enhancing carbon sequestration, these projects could negatively affect freshwater storage via increased ET and reduced soil moisture as in other dryland regions in China (Zhao et al. 2021). The exact contribution of these ecological restoration programs to NWC’s historical TWS depletion, relative to crop expansion, warrants future studies.

Nevertheless, a nexus approach that systematically considers the trade-off among agriculture production, water sustainability, climate change, and economic growth is central to both future government policy making (D’Odorico et al. 2018, Liu et al. 2018, He et al. 2019) and to achieving UN SDG 6—‘ensure access to water and sanitation for all’ (SDGs 2015, Liu et al. 2018).

4.2. Limitation and caveats of this study

TWS contains several hydrological components including surface water, groundwater, soil moisture, and snow water equivalent, each with its own temporal dynamics. It is worth noting that this study did not attempt to attribute the relative contribution of surface water versus groundwater to the TWS depletion. The challenge is the lack of in situ measurements and/or high-quality model simulations of these two components, as well as other components like soil moisture. In addition, ET trends were calculated from GLEAM ET products, which were derived based on satellite observations. Underestimation may appear in the GLEAM ET for irrigated areas, as the irrigation was not directly involved as an input but was partly accounted for by adjusting the soil moisture seasonal dynamics (Miralles et al. 2011). We did not employ the ET estimates from hydrological models with data assimilation like GLDAS, as these estimate, although they may be of good quality in other regions (Chang et al. 2020), are not reliable for NWC, due to the lack of adequate representations of groundwater dynamics, surface water diversion, and irrigation (in terms of irrigation type, amount, and timing that substantially alter the terrestrial water budget especially in growing seasons) (Ozdogan et al. 2010, Zeng and Cai 2018, Zhang et al. 2019, 2020). These various modeling deficiencies also prevented us from running a fully coupled regional land-climate model over NWC to account for the land-atmosphere interactions/feedbacks, e.g. soil moisture—ET—precipitation coupling (Lo and Famiglietti 2013). We thus decided to utilize the parsimonious counterfactual analyses to demonstrate the consequence of crop expansion induced ET increase on the fate of region-wide TWS dynamics. On the other hand, the scarcity of in situ measurements makes them impossible to estimate region-wide water budgets, while freely accessible remote sensing products provide such opportunities at a much larger scale. We acknowledge possible bias related to the GRACE data (Long et al. 2014) in terms of its inherent uncertainties, and propagation of bias/leakage correction. These biases, along with its relatively coarse spatial resolution, prevented the interpretation of the GRACE TWS trend over a pixel-specific basis. Despite these limitations, GRACE observations currently
remain the most efficient and reliable way to obtain regional-scale estimation of the TWS changes (Rodell et al. 2018). Although with potential uncertainties and error margins of our analyses noted above, this study forewarns that the growth of cropland expansion and agricultural production in NWC is highly unsustainable.

5. Conclusions

NWC has been identified as one of the major global hotspots of freshwater depletion in recent years, yet the underlying driver(s) for such depletion remains controversial. Here, based on multiple sources of independent datasets, we confirmed that the enhanced evaporative water loss, resulting from increased irrigation demand to support the continuous cropland expansion, is the most plausible and ultimate cause underlying the region-wide water depletion in this vast dryland region. Our findings have important implications for informing policy making toward SGDs in NWC, especially in the context of future population growth and climate change.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

All the original datasets used in this study are publicly accessible: the TWS dataset is publicly available at https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/; the TRMM precipitation dataset is publicly available at https://disc.gsfc.nasa.gov/datasets/TRMM_3B43_7/summary; the ERA-Interim datasets are publicly available at www.ecmwf.int/en/forecasts/datasets/reanalysis-data/era-interim; the GLEAM ET dataset is publicly available at www.gleam.eu/#datasets; the GLDAS dataset is publicly available at https://disc.gsfc.nasa.gov/datasets?keywords=GLDAS; the GRUN dataset is publicly available at https://figshare.com/articles/dataset/GRUN_Global_Runoff_Reconstruction/9228176; the AI dataset is publicly available at https://cgrarcsi.community/data/global-aridity-and-pot-datibase; the elevation dataset is publicly available at https://earthexplorer.usgs.gov/; the land cover product is publicly available at http://maps.elie.ucl.ac.be/CCI/viewer/download.php; the statistical datasets are publicly available at https://data.stats.gov.cn/english/easyquery.htm?cn=E0103.

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Author contributions

Y S conceived the study. J L and Y S developed the methodology. J L conducted the analyses. J L and Y S interpreted the results, with help from all other coauthors. J L and Y S constructed the initial draft, and other coauthors contributed critically to the subsequent revision of manuscript.

Conflict of interest

Authors declare that they have no competing interests.

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