

Impact of large-scale tree planting in Yunnan Province, China, on the water supply balance in Southeast Asia

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Abstract Along with rapid economic development and population growth, anthropogenic disturbances to natural ecosystems increase the progressively worsening environmental problems in and around water resources, making the potential ecological risks more severe and unpredictable. In order to cope with the increasingly serious issues related to the ecological environment and poverty alleviation, the Government of Yunnan in Southwest China launched a large-scale afforestation campaign (plantation forestry) on the Yunnan–Guizhou Plateau, which is the main source of several major river systems in Southeast Asia. In this study, we use GIS to investigate the impacts of a large-scale afforestation on the water storage balance of Southeast Asia. Results show an expansion of the arid zone in the Yunnan–Guizhou Plateau in recent years, and runoff from rivers has decreased year after year. In contrast to natural forests, planted forests are a characteristic of more water shortages, less rainfall, and higher evapotranspiration rates. Moreover, planted forests

may exacerbate conflicts between humans and nature over water resources. Additionally, with respect to downstream populations affected by the government’s afforestation policy, China has bore the brunt of the resultant water scarcity predicament (approximately 52.29%), followed by Vietnam (26.39%), Laos (6.78%), Cambodia (6.16%), Thailand (4.42%), and Myanmar (3.96%). To alleviate this problem and the potential crises that may result from it, the Government of China should change its policy from its focus on afforestation to promoting natural vegetation conservation practices.

Keywords Afforestation · Water storage · Southwest China · Southeast Asia · Evapotranspiration

Introduction

The Yunnan–Guizhou Plateau was formed by collisions between the Paleo-Tethys and the Tibet–Yunnan “old land” and the Yangtze “old land” during the Paleozoic periods and the Cenozoic Era (Cheng 2007). The plateau is the source of several major river systems in Southeast Asia. These rivers provide potable water to 20% of the world’s population (Cao et al. 2016). Because of its high elevation, the plateau is composed of some of the world’s most fragile ecosystems. In recent years, a large number of planted forests (eucalyptus and rubber trees) were established in Yunnan Province, which has resulted in the development of ecological or environmental problems. This has gradually become an

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issue that ecologists and managers are becoming increasingly concerned with (Schoenbohm et al. 2004).

In comparison, natural ecological systems can better support sustainable development where, on the other hand, anthropogenic-derived ecosystems result in serious environmental problems (Lu et al. 2016). It is, therefore, important to reflect on the mode of resource utilization. The block or depletion of resource utilization on both time and space scales is the major cause of serious environmental problems (Weyerhaeuser et al. 2005). The question of how to establish a new mode of ecological resource management and utilization to promote rational exploitation, recycling, and utilization decisions of resources is an important task in the development of the human society (Gao et al. 2011b).

Impacted by both anthropogenic and natural factors, the Yunnan–Guizhou Plateau has undergone serious environmental degradation (Cao 2015). In order to slow or reverse such environmental degradation and to protect local water resources at the same time, the Government of China launched a massive afforestation campaign in Yunnan Province. From 1949 to 2011, for example, the total afforested area in the province increased to over 1610 km². Furthermore, even though the rate of vegetation cover on the Yunnan–Guizhou Plateau has increased in recent years, few studies have considered the impact of ecological restoration on local water resources (Zhang et al. 2016).

Today, many countries are faced with progressively severe water scarcity problems. It is predicted that 25% of the world's population will experience severe water scarcity in the first quarter of the twenty-first century (Yan et al. 2006). In recent years, almost unrelenting drought events have affected China and parts of South Asia, including Vietnam, Laos, and Myanmar, and millions of people have been subjected to water scarcity issues (Wu et al. 2017). Given that the Yunnan Province borders a number of countries beyond China's borders, water resource shortages in Yunnan Province will obviously have a negative impact on countries situated downstream of the province. The Yunnan–Guizhou Plateau is the main water source for most countries in Southeast Asia; therefore, for those who rely on rivers that originate from the Yunnan–Guizhou Plateau, water resource protection measures implemented by the Government of China have a significant impact on the availability of freshwater. Various studies have pointed out that large-scale water resource protection policies and water transport projects implemented by China have seriously undermined the

availability of water resources to countries situated downstream of the province, including Vietnam, Laos, Democratic Kampuchea, and Thailand (Li and Fox 2012). In addition, the effects of climate change on precipitation and vegetation cover on the Yunnan–Guizhou Plateau will also exacerbate the water scarcity problems for the countries and regions mentioned above. Furthermore, restrictions on water resource availability often result in a competition between native species for available water as well as competition between natural ecosystems and human needs. Droughts in Yunnan Province have been the most serious among all China's provinces in the recent years (Chen et al. 2009). The most serious drought in Yunnan Province struck in 2010, impacting 69,000 km² and 1,200,000 people.

Given the urgent need to address these issues, in this study, we demonstrate the potential impacts of the Government of China's afforestation campaign on available water resources of the Yunnan–Guizhou Plateau and its downstream region, while also advocating that future relevant research must focus on the ecological impacts, such as making changes to the traditional water resource structure by applying ecology principles, forming a new circulation mode through ecological restructuring, and establishing water resource management mechanisms to promote the efficient use of water resources and reducing the impacts on the ecological environment (Gao et al. 2011a). Accordingly, the objectives of this study were to determine where water shortages occurred on the Yunnan Plateau during the past 15 years, to discover the causes of water shortages in these areas, and to ascertain the impacts that water scarcity has had on other countries in Southeast Asia.

Materials and methods

Study area

The study area (21° 09'–29° 15' N, 97° 32'–106° 12' E) is located in Yunnan Province, Southwest China, a region that includes four of Southeast Asia's largest rivers: the Yangtze, Mekong, Salween (known as the Nu River in China), and Red rivers (Fig. 1). It borders the Himalayas and Myanmar (Burma) to the west, Vietnam and Laos to the south, and covers a surface area approximately 39.4 × 10⁴ km². It is situated 1879 m AMSL, with elevations ranging from < 100 m in the

southeastern hilly region to over 6000 m in the Hengduan Mountains in the northwest (Zhu et al. 2011). Its climate is typically subtropical monsoonal, affected by the southwestern and southeastern circulation in summer and northeastern monsoons in winter. Hence, the study region experiences abundant rainfall but uneven spatiotemporal distribution, where mean annual rainfall is approximately 1100 mm. Yunnan Province, being one of China’s most strategically important regions, is located within a critical area where it serves as a bridgehead between the rest of the country and the diverse and complex economies and politics of South and Southeast Asia. Thus, the region has a significant impact on all downstream river systems, and this is not only due to international trade and economic progress between China and its regional neighbors, but it is also due to issues related to water resource conservation, affecting hundreds of millions of people living in the region’s lower river basins.

In recent years, under a background of global climate warming, the average temperature in Yunnan Province rose by 0.66 °C between 1961 and 2008. Moreover, droughts on the Yunnan–Guizhou Plateau have shown increasing and intensifying trends. Recent research has shown a significant increase in the temporal and spatial variation of meteorological droughts in Yunnan Province since the 1970s, and that the intensity of annual meteorological droughts has increased (Chandrasekara et al. 2017).

Data sources

The meteorological data from 2000 to 2014 mainly includes precipitation and temperature. We interpolated this data, collected from meteorological stations, to the entire study area, applying kriging regression (Xiao et al. 2016). The annual evapotranspiration data from 2000 to 2014 (MOD16 global evapotranspiration product) was obtained from the Land Processes Distributed Active Archive Center (<https://lpdaac.usgs.gov/>). The MOD16 evapotranspiration datasets were estimated using the improved ET algorithm of Mu et al. (2011), which is based on the Penman-Monteith equation (Monteith 1965). Ecosystem maps for 2000, 2005, 2010, and 2014 were produced by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, using Landsat-TM and Landsat-ETM+ images (<http://www.irsac.ac.cn>). Surface runoff coefficients of each ecosystem type were acquired from published literatures

(Ouyang et al. 2016). The population density data from 2000 to 2014 was obtained from LandScan Global Population Project, Oak Ridge National Laboratory (ORNL). Digital elevation model (DEM) data originated from the Shuttle Radar Topography Mission. The water resource observed data obtained from China’s water resource bulletin (State Water Agency 2001–2015) was used to verify water resource model’s reliability. The natural and planted forest samples mainly include *pinus yunnanensis* and *p. khasya* forest; evergreen broadleaved forest and rubber were collected from Luo’s research (1996) and Li’s research (2012). Some details concerning the data are listed in Table 1.

Methods

To understand the changes of water resource and its impacts on the lower river basins of the Yunnan–Guizhou Plateau, firstly, we calculated the water resource retained in ecosystems and soil that were established through the principle of water balance (the difference among precipitation, evapotranspiration, and surface runoff), using the revised InVEST model (Ouyang et al. 2016; Xiao and Ouyang 2018).

The water storage is defined as the ability of ecosystems to intercept or store water resources from precipitation, which is calculated by precipitation minus evapotranspiration and surface runoff. The water storage model based on the principle of water balance is presented as follows:

$$WR = P - ET - R_a \tag{1}$$

Where, WR is the water storage retained in ecosystem and soil (mm a^{-1}); P and ET represent the annual precipitation (mm a^{-1}) and annual actual evapotranspiration (mm a^{-1}), respectively; and R_a is the actual surface runoff (mm a^{-1}).

According to other’s research result (Xiao and Ouyang 2018), precipitation intensity obviously affected the magnitude of surface runoff, thus, runoff can be described as below:

$$R = P_h \times \alpha \tag{2}$$

Where, R denotes the surface runoff caused by heavy rainfall (mm a^{-1}); the detail information of α as the surface runoff coefficient was shown in other’s research result (Xiao and Ouyang 2018); and P_h represents the annual heavy rainfall (mm a^{-1}), and it can be estimated as follows:

$$P_h = \sum_{i=1}^n P_d \tag{3}$$

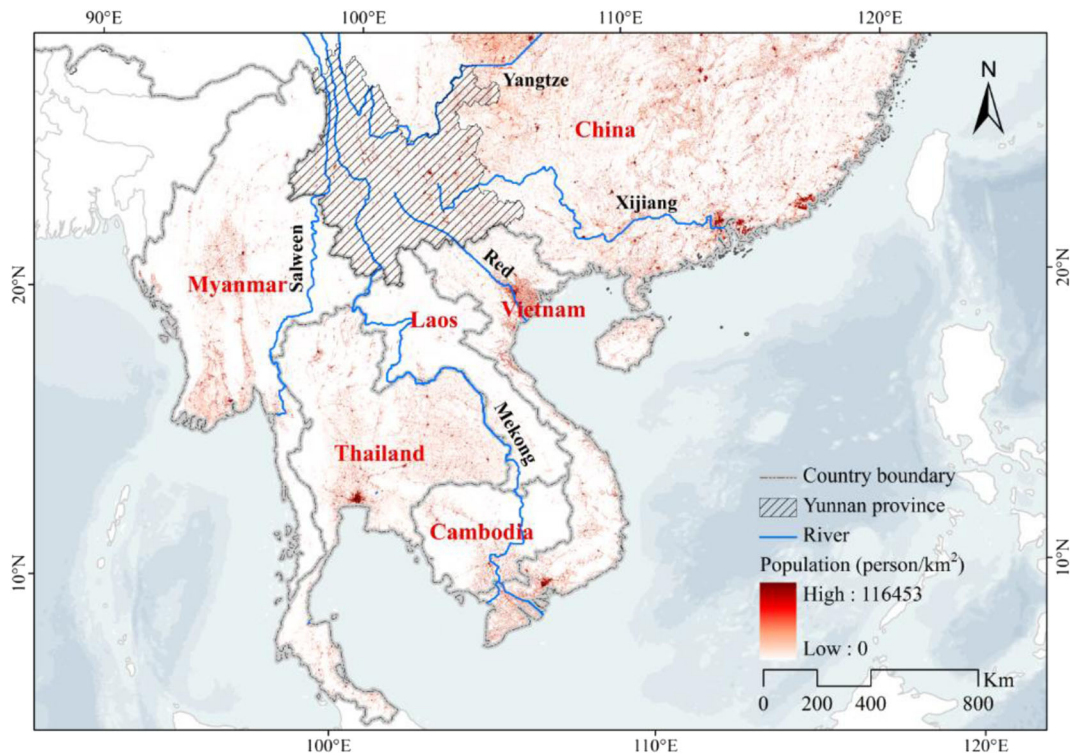


Fig. 1 Map of the main river systems in South Asia that navigate through Yunnan Province

Where, n represents the total days per year (it is equal to 365 or 366 days) and P_d is the daily heavy rainfall, which

is greater than 25 mm by reference to Zhao’s research (2004).

Table 1 Principal data sources

Data name	Data type	Time	Data source
Precipitation (month)	1000 m	2000–2014	Chinese National Metrological Information Center/China Meteorological Administration (NMIC/CMA)
Precipitation (day)	1000 m	2000–2014	Chinese National Metrological Information Center/China Meteorological Administration (NMIC/CMA)
Temperature	1000 m	2000–2014	Chinese National Metrological Information Center/China Meteorological Administration (NMIC/CMA)
Evapotranspiration (ET)	1000 m	2000–2014	Land Processes Distributed Active Archive Center (LP DAAC)
Ecosystem maps	90 m	2000, 2005, 2010, 2014	The Institute of Remote Sensing and Digital Earth of the Chinese Academy of Sciences
Surface runoff coefficients	Parameters	Multi-year average	Ouyang’s research 2016
Vegetation map	1:1,000,000		Institute of BOTANY, Chinese Academy of Sciences
Population	1000 m	2000–2014	LandScan Global Population Project, Oak Ridge National Laboratory (ORNL)
DEM	90 m		The NASA Shuttle Radar Topographic Mission (SRTM)
Water resource observed data	Provinces	2000–2014	China’s water resource bulletin (State Water Agency, 2001–2015)
Socioeconomic data	Counties	2000–2014	Statistical Yearbook (State Statistics Bureau, 2001–2015)
Field-based forest data	Points	Published in 2004, 2012	Luo’s research 1996, Li’s research 2012, and Field survey

Following an assumption similar to that made by Zhang et al. (2001), in reality, the surface runoff would be less than or equal to the difference between precipitation and evapotranspiration ($P - ET$), according to the water balance principle. Therefore, the actual surface runoff can be estimated based on the per-pixel replacement processing using the $P - ET$ value as the judgment condition. The value of the surface runoff for pixel (i, j) is expressed in $R(i, j)$, and the value after dealing with the pixel replacement is expressed in $R_a(i, j)$. The i and j are the row and column number of the pixel.

$$R_{a(i,j)} = \begin{cases} P_{(i,j)} - ET_{(i,j)}, & P_{(i,j)} - ET_{(i,j)} < R_{(i,j)} \text{ (arid area)} \\ R_{(i,j)}, & P_{(i,j)} - ET_{(i,j)} \geq R_{(i,j)} \text{ (humid area)} \end{cases} \quad (4)$$

To verify our model’s regional applicability and reliability, we validated the exported results based on water resource observed data. The simulated results agreed well with the corresponding observed values ($r = 0.915, n = 11, p < 0.01$).

To detect the variation in trends of WR and climatic data during 2000–2014, a least-squares linear regression method was used in our study by fitting a linear equation of variables as a function of time (year). The least-squares linear regression method was applied as follows:

$$y = a + b \times t + \varepsilon \quad (5)$$

Where y represents WR and climatic data, a is the intercept, b is the slope as a proxy of the trend, t is the year, and ε is the residual error. $b > 0$ means an increasing trend, conversely, $b < 0$ denotes a reducing trend. We estimated the significance of trends in time series data using a T test, where a P value < 0.05 was considered significant.

Additionally, to determine the impacts of changes in water storage on local and downstream populations that depend upon water from the Yunnan–Guizhou Plateau, we estimated the affected population of each area by determining the number of downstream beneficiaries of the water storage. Then, the changes of water storage were weighted by the accumulative number of downstream populations to quantify the impacts of water scarcity on downstream regions (Xiao and Ouyang 2018).

$$B_i = WRC_i \times POP_i$$

Where B_i is the impacts of WR change in pixel i ; WRC_i is the change of WR production by pixel i ; and POP_i is the

total population that affected by the reduction of WR flow produced by pixel i .

The contribution of each factor to reductions in water storage can be estimated by the product of the factor’s change and its partial derivative. Thus, the contribution of each factor to changes in water storage can be calculated using the following differentiating equation:

$$dQ = \frac{\partial Q}{\partial P} dP + \frac{\partial Q}{\partial ET} dET + \frac{\partial Q}{\partial R} dR$$

or more briefly:

$$T(Q) = C(P) + C(ET) + C(R)$$

Where $T(Q)$ is the actual linear trend of Q and $C(P)$, $C(ET)$, and $C(R)$ are the contributions of changes in precipitation (P), evapotranspiration (ET), and surface runoff (R), respectively, to the variation in water storage (Q).

The relative contributions of each factor to the water storage change can be calculated as follows:

$$RC(x_i) = \frac{C(x_i)}{T(Q)} \times 100\%$$

Where x_i represents each of the above three variables.

Results

Water shortages

The results from this study showed a decline in water storage throughout most of the entire western region, accounting for 94.08% of the total area (Fig. 2a). Moreover, water storage developed in fluctuation and showed a general decreasing trend from 2000 to 2014 (an annual decrease of 4.57 billion m^3) along with ongoing increases in water consumption (an annual increase of 0.03 billion m^3) (Fig. 2b). Inequalities in hydraulic assets are evident in the human and economic costs associated with extreme drought events (Fig. 2c). In 2010, Yunnan Province suffered one of its worst droughts in 60 years, which lasted for a period of 6 months, affecting agricultural area, population, and livestock, causing a deficiency in potable drinking water for 28,380 km^2 of land, 9.65 million persons (Bulletin of Drought and Flood Disaster in China 2000–2015).

These water shortages must be taken seriously because, if accurate, they will have a devastating effect on international water supplies and water security.

Moreover, the annual average water storage was very low for periods 2005–2009 and 2010–2014, and only 104.72 and 83 billion m³, respectively. Meanwhile, the precipitation was in the low range (395.97–428.43 billion m³) and evapotranspiration was in the high range (305.63–309.12 billion m³) (Table 2).

Characteristics of planted forest and natural forest drought resistant

We estimated changes in water storage resulting from climate change and anthropogenic activities using the methods described above. Results indicated that precipitation factors had the greatest contribution to water resource shortages (89.8% for the entire region), followed by evapotranspiration and surface runoff (8.7% and 1.5%, respectively). Despite the dominant contribution of climate change to water storage, anthropogenic impacts were too significant to ignore. In particular, the Government of China launched a series of afforestation projects in recent years, which are among the world's largest government-financed expenditures associated with environmental protection. Yunnan Province, being the second largest afforested area in China, is undergoing enormous alterations in ecosystem structure and functions.

Regression analysis (Fig. 3a, b) showed a significant ($p < 0.01$) positive relationship between changes in water storage and changes in precipitation ($R^2 = 0.518$) and a significant negative relationship between water storage and evapotranspiration ($R^2 = 0.397$) over the past 15 years. However, as Fig. 3 illustrates these relationships showed some differences in each forest type. Precipitation and evapotranspiration accounted for greater variation in water storage in natural forests (72.3 and 19.8%, respectively) compared to planted forests (34.6 and 18.4%, respectively), which indicated that, in addition to climate change, anthropogenic activities had a strong impact on planted forests. At the same time, compared to natural forests, more water shortages, less rainfall, and higher evapotranspiration rates could also be observed in planted forests (Fig. 3c), which suggested that planted vegetation communities on the Yunnan–Guizhou Plateau may aggravate the frequency of extreme drought events.

Impacts of water scarcity on downstream regions

Given the potential threat to international water supplies and water security, the negative impacts associated with water shortages originating from China's Yunnan–Guizhou Plateau and the surrounding countries in Southeast Asia must also be addressed. With regard to the downstream populations, this study found that China suffered the greatest overall water scarcity impacts (approximately 52.29%), followed by Vietnam (26.39%), Laos (6.78%), Cambodia (6.16%), Thailand (4.42%), and Myanmar (3.96%) (Fig. 4). Changes in impacts of water scarcity exhibited high heterogeneity in spatial distribution, for which the northeastern Yunnan–Guizhou Plateau had a more significant impact on China compared to the surrounding countries (Fig. 4). Areas significantly impacted (illustrated by the darker colors in the maps provided in Fig. 4), covering the upper reaches of all the major rivers, also significantly impact lower areas as per the large population affected in the lower river basin. Moreover, we also found that changes in precipitation had the greatest contribution to water shortages (85.87–89.77%), followed by evapotranspiration (8.73–13.52%) and surface runoff (0.78–1.5%). However, the contributions of the main factors that control water scarcity varied for the different countries affected. In particular, evapotranspiration had a greater contribution in Myanmar (13.25%), Thailand (12.57%), Cambodia (12.97%), and Laos (12.97%), but not in China and Vietnam, which were both less than 10%. The large number of rubber tree (*Hevea brasiliensis*) plantations that are effectively more simplified and fragile artificial ecosystems, have over time invaded the original natural vegetation habitats through human exploitation, accelerating local water losses due to their higher evapotranspiration rates, which will benefit by raising the photosynthetic rate to maintain a strong competitive advantage.

Discussion

The drought in Yunnan Province

Generally speaking, drought is one of the most serious natural disasters affecting economic development and agricultural production. Many studies have shown that drought disasters are due to a combination of meteorological factors (Moosdorf and Oehler 2017). With the

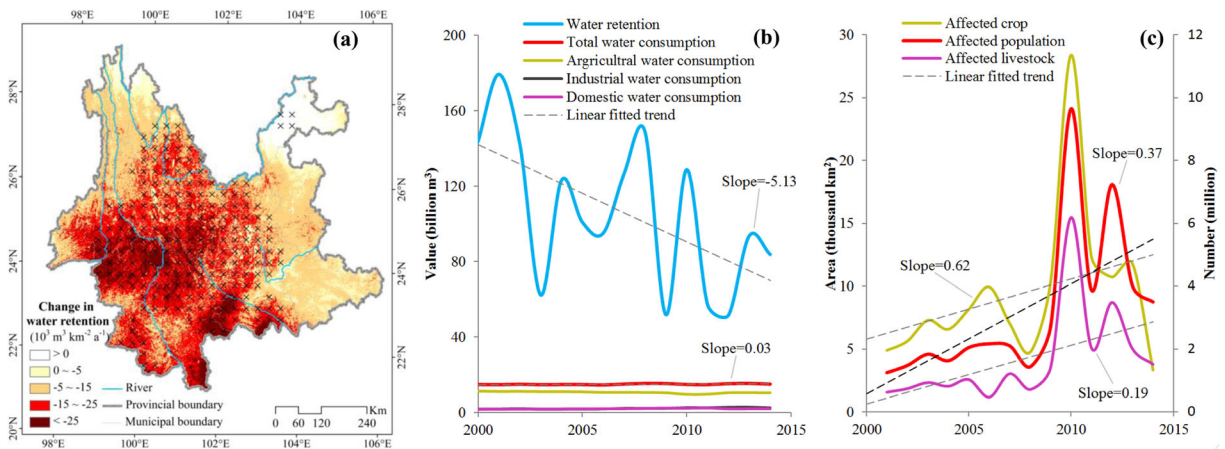


Fig. 2 a Spatial variation trends in water retention, and b the corresponding time line chart representing total changes and c impacts of drought events from 2000 to 2014 in Yunnan Province.

Cross marks in the spatial variation map indicate areas of significant change ($p < 0.05$)

increasing global climate change, extreme weather events occur more frequently, and the impact of drought on agricultural production is increasing day by day along with increasing production losses. This study focuses on improvements to the drought index and the analysis of its temporal and spatial variation (Kong et al. 2015). We provide new evidence on the characteristics of decreasing water storage caused by drought in the Yunnan–Guizhou Plateau. By comparing data from 2000 to 2015 (Fig 2), we found a clear evidence that water storage in the Yunnan–Guizhou Plateau developed in fluctuation and has exhibited a decreasing trend. Reasons for this are that declining water storage could be found in almost the entire western region of the plateau, accounting for 94.08% of the total area. This demonstrates that the degree of droughts in the Yunnan–Guizhou Plateau is increasing. Yunnan Province is located on the low-latitude plateau of China (Miao et al. 2015). The climate differs greatly per region, having distinct dry and wet seasons. The droughts in this region of China are also characterized by the coexistence of

clearly stable large areas and local areas (Sweet et al. 2017). As a result of less precipitation, long continuous droughts, and the late start of the rainy season, western Dali and Chuxiong cities are the main areas of perennial droughts in Yunnan Province (Sun et al. 2016). Moreover, dry and hot valleys, such as those in western Lingchang City, the southern section of the Honghe Hani and Yi Autonomous Prefecture, and Karst areas of eastern Qujing and Wenshan cities, represent Yunnan Province’s local perennial drought areas (Miao et al. 2016). These findings clearly show that the causes of drought are complex and are composed of many factors, which mainly include precipitation, evapotranspiration, and the duration of drought (Stagge and Moglen 2017).

Probable causes of the drought in Yunnan Province

Our results clearly showed that water consumption was much higher for planted forests than for natural vegetation. Afforestation, used for purposes of environmental and water resource restoration on the Yunnan–Guizhou

Table 2 Characteristics of water storage, precipitation, and evapotranspiration in different periods (average unit: billion m^3 ; C_v unit: %)

Series	Water storage		Precipitation		Evapotranspiration	
	Average	C_v	Average	C_v	Average	C_v
2000–2004	130.25	0.33	452.72	0.11	302.91	0.01
2005–2009	104.72	0.35	428.43	0.11	309.12	0.01
2010–2014	83	0.37	395.97	0.08	305.63	0.02
2000–2014	105.99	0.38	425.71	0.11	305.89	0.02

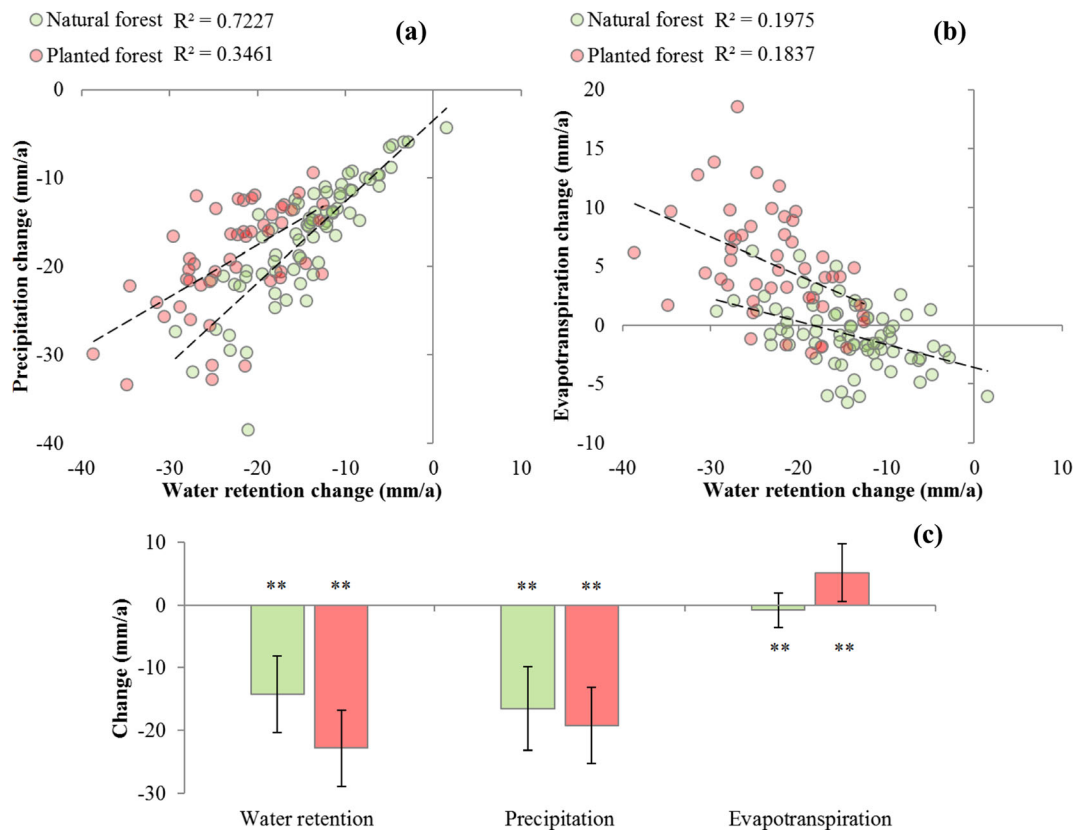


Fig. 3 **a** Relationships between changes in water retention and precipitation, **b** and changes in evapotranspiration for each forest type. Each data point in the figure represents a 15-year slope value (2000–2014). R^2 is the coefficient of determination of the linear functions between water retention and precipitation and water

retention and evapotranspiration. **c** Annual trends in water retention, precipitation, and evapotranspiration for each forest type. Asterisks above or below the bars indicate that the trend is statistically significant at $p < 0.01$. Error bars represent the standard deviation

Plateau, appeared to only exacerbate the current water resource shortages. Any further deterioration in water shortages would have an impact on human welfare and the environment at large, and it would seriously restrict economic development. Recent studies have shown that the large-scale destruction of the original plantation forests, such as eucalyptus and rubber tree forests (Fig. 5), would fragment rivers and make droughts more severe. Climate change and large areas of planted forests cause a decline in the volume of a runoff of the main rivers in Yunnan Province. In particular, the southwestern region of the province (the Xishuangbanna Dai Autonomous Prefecture, Pu'er City, etc.) has a large number of rubber plantations, and the total area of cultivation in 2014 was approximately 5800 km². In the short-term, this will reduce the amount of available water for human subsistence, economic development, and environmental protection (Cao 2008a). Any plan based on the assumption that water in the upstream

region of Yunnan Province is consumed for local development is foolish. Moreover, hydrological data on all rivers entering Yunnan Province are now extremely scarce; thus, it is crucial that we obtain data to support future water management decisions in Yunnan Province (Herron et al. 2002).

When the amount of rainfall is less than evapotranspiration, vegetation (including trees) will be forced to survive through groundwater extraction. This will lead to the depletion of near-surface water and a decline in groundwater levels, thereby reducing water resource availability for all vegetation. Yunnan Province borders a number of countries, and water shortages in the province will obviously result in some negative impacts to downstream regions. The world's increasing population and rapidly developing economies have resulted in an increase in water consumption, causing further depletion and the expansion of water resource scarcity. Such conditions could lead to the potential of "fresh water

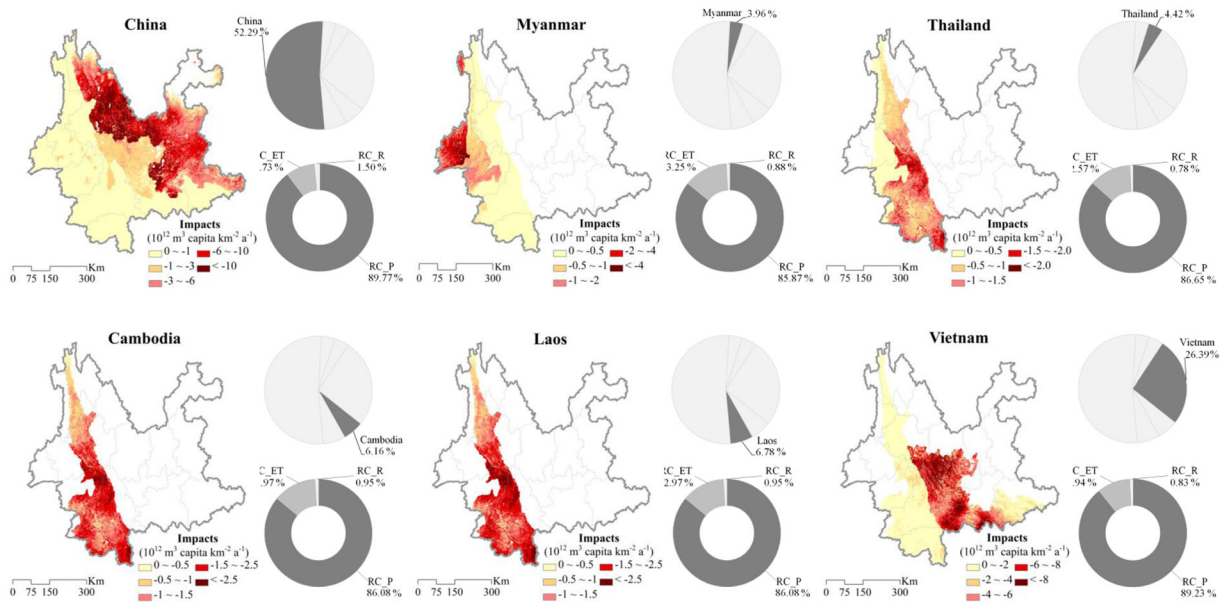


Fig. 4 Maps of the study area showing the spatial patterns of impacts on the reduction in water retention on downstream populations affected in China, Myanmar, Thailand, Cambodia, Laos, and Vietnam, respectively (the darker the color, the greater the water scarcity impact on downstream populations). Pie charts

describe the percentage of impacts for each country. Doughnut charts represent the relative contribution of precipitation (RC_P), evapotranspiration (RC_ET), and surface runoff (RC_R) to the reduction in water retention

wars” between countries that will have to fight for water in the future, such as China and Vietnam and China and Burma (Cao and Zhang 2015). Yunnan Province is the source of the main river systems in many countries within Southeast Asia; thus, it has become a political hot spot. For example, there have already been disputes between China and Burma over the construction of dams on the Nu River in recent years. Therefore, in addition to the environmental problems that will result from the increasing need for potable water, water resource scarcity caused or degraded by large-scale afforestation projects in the fragile ecological zone of Yunnan Province may also trigger regional conflicts (Amichev et al. 2012). In brief, the severe droughts that have occurred in Yunnan Province have led to water access difficulties in countries downstream of the province. Before the intervention, however, we must bear in mind that our behavior is constrained by ecosystem response because ecosystems are complex and not yet fully understood (Cao 2008b).

Impacts of drought on downstream countries

The Yunnan–Guizhou Plateau is home to many important rivers that cross international borders, such as the

Nu River, the Lancang River, and the Red River, and transboundary water security problems and disputes are becoming increasingly more prominent. Given that approximately two thirds of Vietnam’s total water resources depend on neighboring countries, China’s exit runoff volume accounts for approximately 39% of the total runoff volume of the Red River. Under a background of climate change, the runoff volume in the past 50 years has shown a decreasing trend, exacerbating the contradiction between the supply and demand for water resources. In 2010, the entire basin experienced severe drought, and the water level of the Red River in Vietnam dropped to a 100-year low, which had a great impact on that country. Some Vietnamese scholars believe that cascade hydropower development, that has taken place in the upper reaches of China, intensified downstream droughts. Therefore, it is urgent to conduct studies on changes in drought characteristics for rivers that cross international borders to provide a scientific basis for the utilization and management of transboundary water resources (Vadell et al. 2016). We found that droughts in Yunnan Province had the greatest impact on China (approximately 52.29%), followed by Vietnam (26.39%), Laos (6.78%), Kampuchea (6.16%), Thailand (4.42%), and Burma (3.96%) (Fig. 4). Therefore,

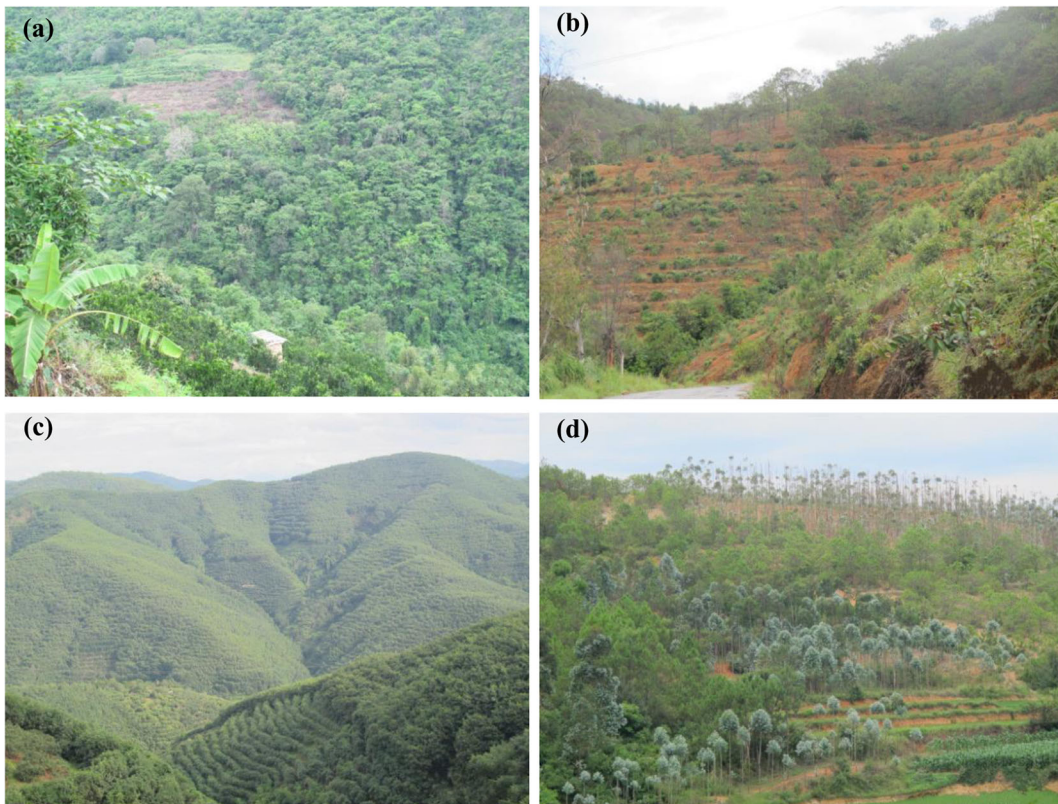


Fig. 5 Photographs of deforestation and afforestation in Yunnan Province (2014). **a** Old-growth forest degradation by illegal charcoal burning operations near Honghe County; **b** ecological forest degradation by fruit tree plantations around Yilong Lake in

Shiping County; **c** the many rubber tree plantations in the Wild Elephant Valley in Jinghong City; **d** a eucalyptus plantation in the vicinity of the Wuliang Mountain Nature Reserve in Jingdong City

we should clarify the core issues related to transboundary water resources, correct traditional inherent modes of thinking, and explore possible frameworks for cooperation in the future. In dealing with issues related to transboundary water resources in the future, Southeast Asia should move beyond the traditional “scarcity-conflict” paradigm and potentially integrate a more eastern inclusiveness and wisdom practices.

For the rational use and the coordinated management of transboundary water resources in the context of global climate change, findings from this study report on the nonlinear factors that influence them. Research on transboundary water allocation in the past 20 years suggests that the development of a reasonable water resource allocation model is more efficient and cost-effective than conflict resolution. The most important factor in reducing risks of conflict is the sustainable and fair allocation of transboundary water resources. Moreover, the allocation of transboundary water resources and international cooperation are the key to ending

conflicts and rebuilding regional mutual trust, security, and development. Lastly, cooperation in resolving differences should focus on water demands or the allocation of package benefits for the equitable distribution of benefits is far more likely to be beneficial to all (Wang et al. 2014).

Water resources are important strategic resources associated with national security. The transnational nature of transboundary river systems makes them rich in geo-economic and geopolitical connotations. The key in maintaining good international relationships is to determine how to properly resolve disputes over international river resources. After oil, water resources have become the new strategic resource. Competition over the usage rights of scarce water resources may lead to domestic and international conflicts; thus, the water resource crisis is playing a more and more significant role in international relations. It is important to note that most problems between countries within international river basins are associated with water resources, that is, those

related to national political stability, regional security, economic prosperity, environmental protection, and sustainable development. This exacerbates social instability and leads to conflict (Marey-Perez and Rodriguez-Vicente 2009).

Conclusions

Results from this study demonstrated that whatever water resource measure is taken on the Yunnan–Guizhou Plateau, the key objectives are to protect its water resources and to improve water use efficiency. Achieving this goal involves a holistic approach that requires careful consideration of the impact of each management policy on water resources and the livelihood of the people and the ecosystems that depend on such water resources. Governments must seek favorable approaches from which to benefit the citizens of their countries, the citizens of their neighbors, and the natural ecosystems that support them.

China and other countries in Southeast Asia that are affected by water resources that derive from the Yunnan–Guizhou Plateau must without delay find ways in which to cooperate and agree on the allocation of water resources. The best way to in which reduce artificial forest area and introduce a more effective approach in reestablishing the forests is to restore natural forest systems. The positive effect of protecting natural vegetation will promote the restoration of the ecological environment and prevent it from being irreversibly degraded. It is hoped that our governments will find better ways to protect water resources and implement more advanced technologies and methods (such as drip irrigation) to protect water resources and stimulate social and economic development. However, the primary goal must be to protect the water resources of the Yunnan–Guizhou Plateau and to increase its efficiency of use.

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References

- Amichev, B. Y., Kurz, W. A., Smyth, C., & Van Rees, K. C. J. (2012). The carbon implications of large-scale afforestation of agriculturally marginal land with short-rotation willow in Saskatchewan. *Global Change Biology Bioenergy*, 4, 70–87.
- Cao, S. (2008a). Impact of spatial and temporal scales on afforestation effects: response to comment on “why large-scale afforestation efforts in China have failed to solve the desertification problem”. *Environmental Science & Technology*, 42, 7724–7725.
- Cao, S. (2008b). Response to comment on “why large-scale afforestation efforts in China have failed to solve the desertification problem”. *Environmental Science & Technology*, 42, 8166–8166.
- Cao, S. (2015). Evolution of a political industry with examples from Chinese history. *Time & Society*, 26, 384–398.
- Cao, S., & Zhang, J. (2015). Political risks arising from the impacts of large-scale afforestation on water resources of the Tibetan Plateau. *Gondwana Research*, 28, 898–903.
- Cao, S., Zhang, J., Chen, L., & Zhao, T. (2016). Ecosystem water imbalances created during ecological restoration by afforestation in China, and lessons for other developing countries. *Journal of Environmental Management*, 183, 843–849.
- Chandrasekara, S., Prasanna, V., & Kwon, H. H. (2017). Monitoring water resources over the Kotmale reservoir in Sri Lanka using ENSO phases. *Advances in Meteorology*, 2017, 1–9.
- Chen, X., Zhang, X., Zhang, Y., & Wan, C. (2009). Carbon sequestration potential of the stands under the grain for green program in Yunnan Province, China. *Forest Ecology and Management*, 258, 199–206.
- Cheng, Q. (2007). Mapping singularities with stream sediment geochemical data for prediction of undiscovered mineral deposits in Gejiu, Yunnan Province, China. *Ore Geology Reviews*, 32, 314–324.
- Gao, Y., Wang, Y., Zhang, G., Xia, J., Mao, L., et al. (2011a). An approach for assessing soil health: a practical guide for optimal ecological management. *Environmental Earth Sciences*, 65, 153–159.
- Gao, Y., Zhong, B., Yue, H., Wu, B., & Cao, S. (2011b). A degradation threshold for irreversible loss of soil productivity: a long-term case study in China. *Journal of Applied Ecology*, 48, 1145–1154.
- Herron, N., Davis, R., & Jones, R. (2002). The effects of large-scale afforestation and climate change on water allocation in the Macquarie River catchment, NSW, Australia. *Journal of Environmental Management*, 65, 369–381.
- Kong, D., Miao, C., Borthwick, A. G. L., Duan, Q., Liu, H., Sun, Q., Ye, A., di, Z., & Gong, W. (2015). Evolution of the Yellow River Delta and its relationship with runoff and sediment load from 1983 to 2011. *Journal of Hydrology*, 520, 157–167.
- Li, Z., & Fox, J. M. (2012). Mapping rubber tree growth in mainland Southeast Asia using time-series MODIS 250m NDVI and statistical data. *Applied Geography*, 32(2), 420–432.
- Lu, C., Zhao, T., Shi, X., & Cao, S. (2016). Ecological restoration by afforestation may increase groundwater depth and create

- potentially large ecological and water opportunity costs in arid and semiarid China. *Journal of Cleaner Production*.
- Luo, T. X. (1996). Patterns of net primary productivity for Chinese major forest types and its mathematical models. *Chinese Academy of Sciences*. (in Chinese)
- Marey-Perez, M. F., & Rodriguez-Vicente, V. (2009). Forest transition in northern Spain: local responses on large-scale programmes of field-afforestation. *Land Use Policy*, 26, 139–156.
- Miao, C., Ashouri, H., Hsu, K. L., Sorooshian, S., & Duan, Q. (2015). Evaluation of the PERSIANN-CDR daily rainfall estimates in capturing the behavior of extreme precipitation events over China. *Journal of Hydrometeorology*, 16, 1387–1396.
- Miao, C., Sun, Q., Duan, Q., & Wang, Y. (2016). Joint analysis of changes in temperature and precipitation on the Loess Plateau during the period 1961–2011. *Climate Dynamics*, 47, 3221–3234.
- Monteith, J. L. (1965). Evaporation and environment. *Symposium of the society of experimental biology*, 19, 205–224.
- Moosdorf, N., & Oehler, T. (2017). Societal use of fresh submarine groundwater discharge: an overlooked water resource. *Earth-Science Reviews*, 171, 338–348.
- Mu, Q., Zhao, M., & Running, S. W. (2011). Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment*, 115, 1781–1800.
- Ouyang, Z. Y., Zheng, H., Xiao, Y., et al. (2016). Improvements in ecosystem services from investments in natural capital. *Science*, 352(6292), 1455–1459.
- Schoenbohm, L. M., Whipple, K. X., Burchfiel, B. C., & Chen, L. (2004). Geomorphic constraints on surface uplift, exhumation, and plateau growth in the Red River region, Yunnan Province, China. *Geological Society of America Bulletin*, 116, 895–909.
- Stage, J. H., & Moglen, G. E. (2017). Water resources adaptation to climate and demand change in the Potomac River. *Journal of Hydrologic Engineering*, 22, 04017050.
- State Water Agency, (2001-2015). China Water Resources Bulletin. China Water Power Press, Beijing (In Chinese).
- State Statistics Bureau, (2001-2015). China Statistical Yearbook. China Statistics Press, Beijing (In Chinese).
- Sun, Q., Miao, C., & Duan, Q. (2016). Extreme climate events and agricultural climate indices in China: CMIP5 model evaluation and projections. *International Journal of Climatology*, 36, 43–61.
- Sweet, S. K., Wolfe, D. W., DeGaetano, A., & Benner, R. (2017). Anatomy of the 2016 drought in the northeastern United States: implications for agriculture and water resources in humid climates. *Agricultural and Forest Meteorology*, 247, 571–581.
- Vadell, E., de-Miguel, S., & Peman, J. (2016). Large-scale reforestation and afforestation policy in Spain: A historical review of its underlying ecological, socioeconomic and political dynamics. *Land Use Policy*, 55, 37–48.
- Wang, Z. J., Jiao, J. Y., Su, Y., & Chen, Y. (2014). The efficiency of large-scale afforestation with fish-scale pits for revegetation and soil erosion control in the steppe zone on the hill-gully loess plateau. *Catena*, 115, 159–167.
- Weyerhaeuser, H., Wilkes, A., & Kahrl, F. (2005). Local impacts and responses to regional forest conservation and rehabilitation programs in China's northwest Yunnan province. *Agricultural Systems*, 85, 234–253.
- Wu, J., Miao, C., Zhang, X., Yang, T., & Duan, Q. (2017). Detecting the quantitative hydrological response to changes in climate and human activities. *Sci Total Environ*, 586, 328–337.
- Xiao, Y., Ouyang, Z. Y., Xu, W. H., Xiao, Y., Zheng, H., & Xian, C. F. (2016). Optimizing hotspot areas for ecological planning and management based on biodiversity and ecosystem services. *Chinese Geographical Science*, 26(2), 256–269.
- Xiao, Y., & Ouyang, Z. Y. (2018). Spatial-temporal patterns and driving forces of water retention service in China. *Chinese Geographical Science*, 1–12.
- Yan, D. P., Zhou, M. F., Wang, C. Y., & Xia, B. (2006). Structural and geochronological constraints on the tectonic evolution of the Dulong-Song Chay tectonic dome in Yunnan Province, SW China. *Journal of Asian Earth Sciences*, 28, 332–353.
- Zhao, T. Q. (2004). Research on China terrestrial ecosystem services and their valuation. *Chinese Academy of Sciences*. (in Chinese).
- Zhang, L., Dawes, W. R., & Walker, G. R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37(3), 701–708.
- Zhang, J., Zhao, T., Jiang, C., & Cao, S. (2016). Opportunity cost of water allocation to afforestation rather than conservation of natural vegetation in China. *Land Use Policy*, 50, 67–73.
- Zhu, F., Qu, L., Fan, W., Qiao, M., Hao, H., & Wang, X. (2011). Assessment of heavy metals in some wild edible mushrooms collected from Yunnan Province, China. *Environmental Monitoring and Assessment*, 179, 191–199.